Is Net Zero Enough for the Material Production Sector?

Analysing the decarbonisation pathways for key material sectors and their ability to meet global carbon budgets

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ZERO WASTE EUROPE

Contents

Report for

ZERO WASTE EUROPE

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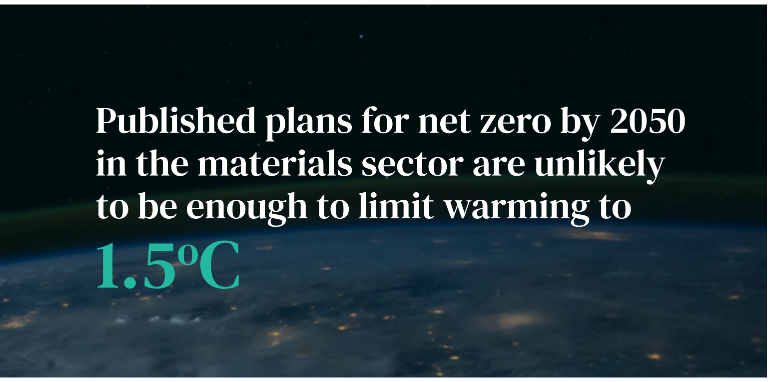
Executive Summary

The IPCC's 2021 Sixth Assessment Report (AR6) estimates that there is a 67% chance of global warming staying within 1.5°C of pre-industrial levels if cumulative global greenhouse gas (GHG) emissions stay below 400 $GtCO_2e$.[i] Current trajectories suggest that this budget will be depleted within the next 10 years if growth rates are maintained. Whilst the IPCC has also stated there is a need for global emissions to reach net zero by 2050—and many organisations throughout the world are working towards this—the concept of a 'carbon budget' has yet to gain as much recognition.

Emissions from the material production sector – resource extraction and processing of raw materials – currently comprise approximately 25% of global emissions, and are therefore of significant importance in reducing emissions in line with this global carbon budget. Current production and consumption trajectories indicate global material use is predicted to double from 2015 to 2060; hence, mitigating the GHG emissions from these sectors is likely to present a significant challenge.



The industries with the highest contribution to this sector are **aluminium, concrete, steel and plastics**. The production of these four materials alone is currently responsible for 78% of GHG emissions from the material production sector. Some of these industries have produced a net zero pathway to meet net zero by 2050 and this report has reviewed each industry's pathway, and modelled whether these will reduce emissions quickly and deeply enough to stay within this budget.

When considering the urgency of reducing GHG emissions there is a possibility that, despite the aims of the net zero pathways, the cumulative carbon emissions budget will be exceeded due to the risks associated with deploying unproven technologies in some sectors. This research aims to allocate a risk factor associated with each intervention and quantify how this influences the likelihood of overshooting the remaining carbon budget. It also attempts to determine whether the overshoot can be reduced by accelerating the adoption model deployed for technological interventions.

[i] The carbon budgets in the IPCC's AR6 refer to CO_2 emissions only, but account for the global warming effect of non-CO_2 emissions. Therefore, this report uses a unit of CO_2e.

Results

The main conclusion of this research is that **published plans for net zero by 2050 in the materials sector are unlikely to be enough to limit warming to 1.5°C.** Likely trajectories show that the result could be as high as 2°C.

More specifically, **the impact of deploying abatement technologies after 2030 is substantially less effective than more near-term, widespread, commercial deployment.**

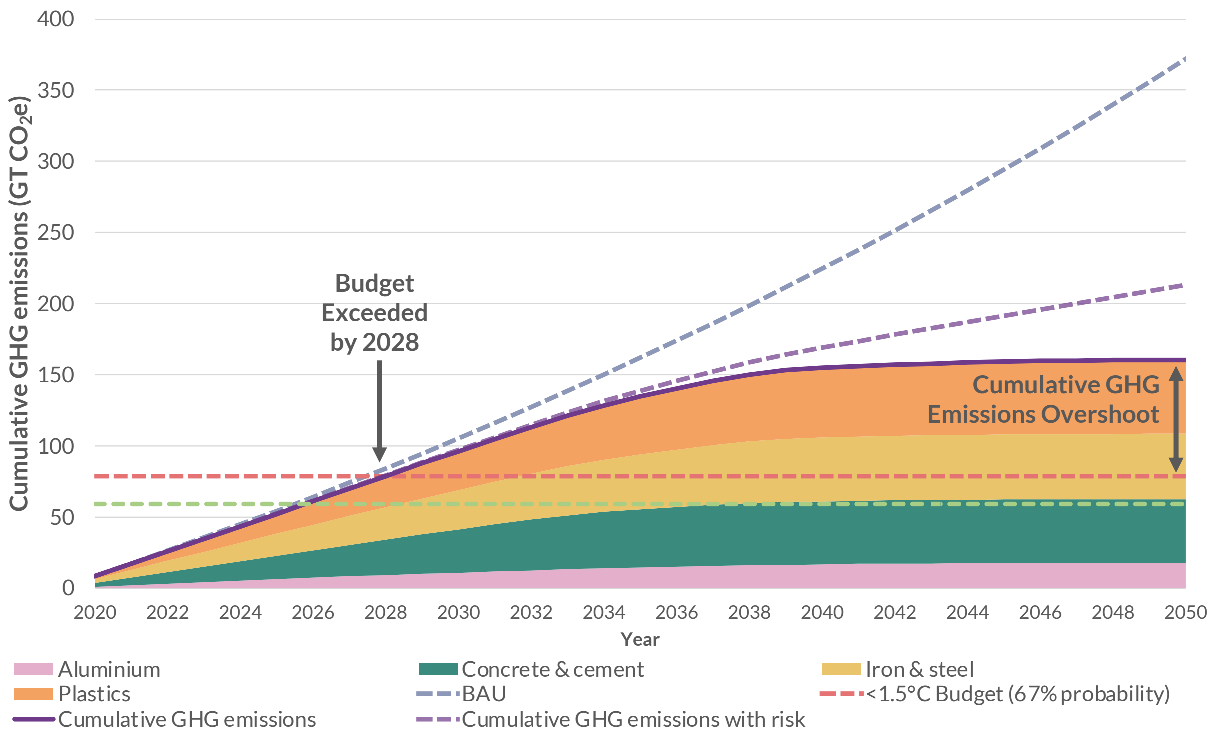
Taking a Business as Usual (BAU) approach to materials production will lead to exceeding the budget by almost five times and result in a trajectory towards warming of 2.5°C. For the plastics industry alone, this could be as high as 3.5°C. Current industry net zero roadmaps bring the difference to double the budget and a warming of around 1.7°C – although with technological risk factored in, this could be as high as 2°C. The plastics industry currently does not have a roadmap to net zero, but projections for this study suggest that a trajectory of 2.2°C is possible even with aggressive decarbonisation.

If the other ~75% of the global GHG emissions from non-material sectors (primarily from energy use in transport and buildings) can remain within budget, the material sector alone would be responsible for reaching 1.6°C under the expected deployment scenario. It is therefore important to also understand the interconnectedness across all global GHG emissions for carbon budgeting to be explored in more detail.

The risk level associated with the realisation of decarbonisation interventions (factoring in the uncertainty around technological innovations) also make it possible that the emissions reductions achieved in practice will be less than predicted, and therefore the chance of overshooting the remaining carbon budget becomes more likely (Figure E.1.1).

The risk level varies by industry. For the aluminium sector, a rapid adoption of existing technologies may bring the sector close to achieving the carbon budget but would involve reversing a trend towards fossil fuel use. The cement and plastics industries respectively rely on the rapid deployment of CCUS and a fundamental shift to bio-based feedstocks; examples of high risk, structurally disruptive interventions that are not currently transitioning rapidly enough. Equally, the steel industry will be reliant on hydrogen, which in not only yet to be produced at scale but will also be highly sought after within other industries.

Figure E.1.1: Cumulative GHG Emissions for the Four Sectors



Recommendations

Following on from the realisation that net zero by 2050 is not likely to be enough to limit warming to 1.5°C, is the requirement for policy mechanisms to promote the implementation of sector-specific measures to accelerate reductions in GHG emissions. Key to this is the recognition that:

- net zero targets should be replaced with 1.5°C – aligned carbon budgets – the setting of these in an equitable way will be a key part of the challenge here;
- it is important to encourage rapid, near-term investment by industry to adjust their current projected timelines. This means that alongside the drive for increasing circularity, reducing primary GHG emissions should be a priority as well;
- there will be a need to drive increased investment in research, development and deployment of electrified processes, green hydrogen, and CCUS; and,
- faster action will be required. By 2040, most if not all interventions must have reached maturity and market saturation across all material sectors. This will likely mean that any significant policies that will drive these changes should be in place by 2030 at the latest.

However, these policies only serve to amend the current business model of continued material production, which is inherently unsustainable. Therefore, these policies need to be supplemented to reduce the risk of under-delivering on GHG emission reductions and improve the likelihood of remaining within the carbon budget. To further reduce the risk of overshooting the global carbon budget, **the rate of increase in material consumption needs not only to be reduced but, in all sectors, reversed.** Key policy interventions should consequently focus on measures that;

- reduce material consumption; and/or,
- drive a shift in material consumption to less carbon-intensive sectors.

High recycling rates and circularity at the material level has its limitations – when *material circularity* reaches its limits, *product circularity* should be the focus which must also go beyond waste prevention as a metric for success. This will likely be in the form of greatly increased reuse, which is why **it is imperative that policies related to resource use are integrated with those on waste, recycling and product design.**

Finally, some consideration also needs to be given to material switching, and the extent to which this may be linked to an increase in demand for materials that are grown, rather than extracted from the ground. Timber as an alternative to concrete, plastics being replaced by paper products, or the move towards bio-based feedstocks are common actions— **this means that, from a policy perspective, there will need to be an increasing overlap between material resources and the bioeconomy.** Addressing one without consideration of the other will lead to unintentional trade-offs. Competition for land use in the future between resources for materials, fuels and food whilst focusing on habitat protection is a key issue that needs to be discussed holistically rather than compartmentalised. Policy makers need to be aware of these interlinkages when designing measures to accelerate the path to net zero.

1.0

Introduction & Background

There is global consensus that a rapid reduction in greenhouse gas (GHG) emissions is critical to limit global warming by 2050 to 1.5°C above pre-industrial levels, as recommended by the Paris Agreement in 2015. This Agreement brought nearly all nations together in a common cause to undertake ambitious efforts to combat climate change. Since then, the IPCC AR6 reports in 2021/22 have underscored how the targets outlined in pledges from countries' Nationally Determined Contributions are insufficient to limit global warming to within 1.5°C by 2050.

The split of global GHG emissions between sectors can be analysed to identify where and how emissions reductions policies should be tailored. GHG emissions from the material production sector – resource extraction and processing of raw materials into major materials including iron and steel, aluminium, cement, chemical products, and pulp and paper – is estimated to account for approximately 25% of global emissions.[1] Current production and consumption trajectories indicate global material use is predicted to double from 2015 to 2060[2]; mitigating the GHG emissions from these sectors is therefore likely to present a significant challenge.

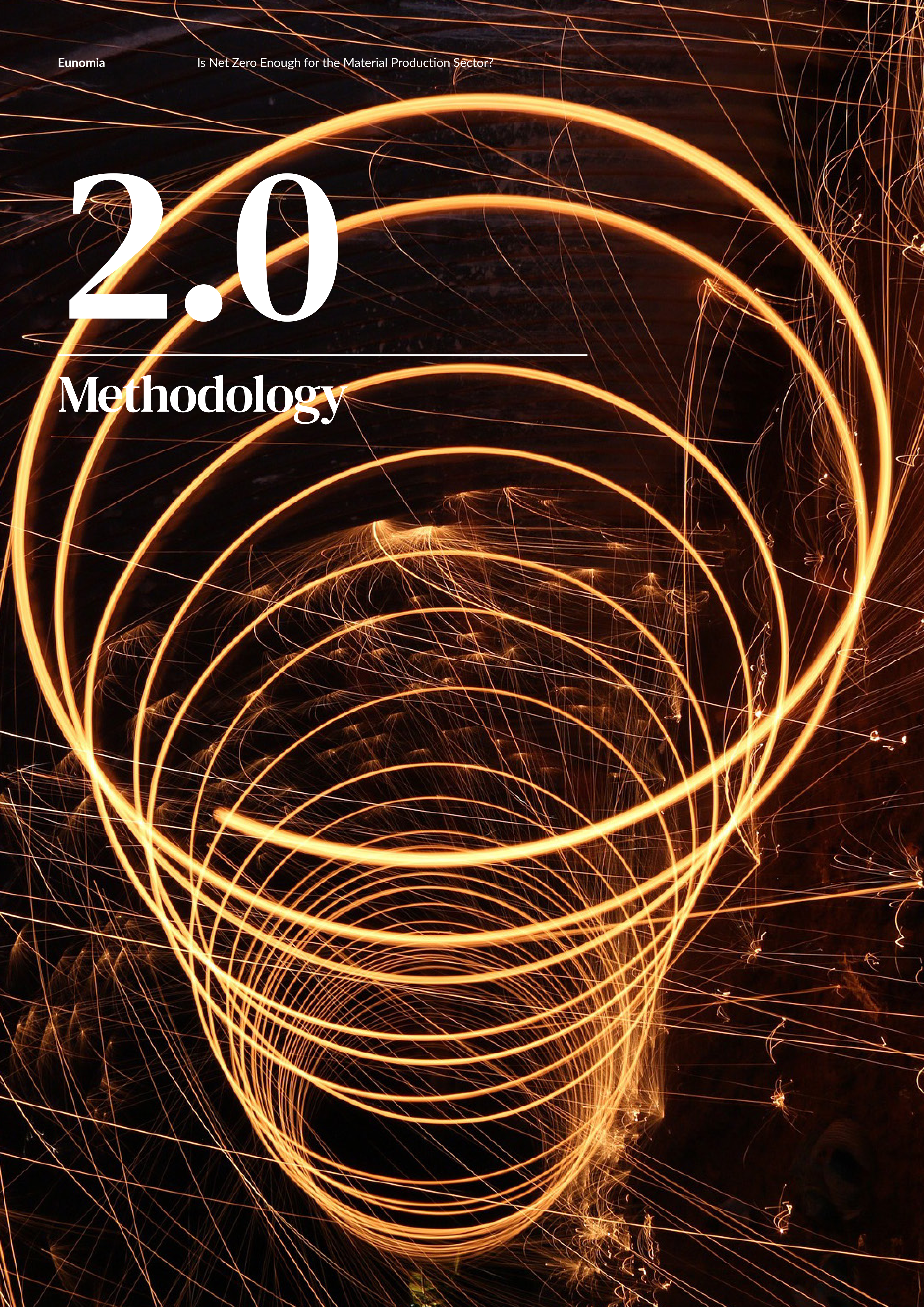
Despite increasing acknowledgement that decarbonisation is necessary, and the proliferation of 'net zero' policies for companies, sectors and countries, there remains a dissonance between what is required to limit warming, and the measures being taken to enact this. This paper investigates whether the decarbonisation interventions outlined in the net zero pathways of key material-producing sectors are sufficient to reduce emissions rapidly enough to help limit global warming to within 1.5°C by 2050.

There is a possibility that the cumulative carbon emissions budget will be exceeded due to the risks associated with deploying unproven technologies in some sectors. Consequently this research also aims to quantify the risk associated with each decarbonisation intervention and how it influences the likelihood of overshooting the remaining carbon budget. In addition, the research aims to determine whether the projected overshoot can be reduced by manipulating the adoption model deployed for technological interventions (exponential, linear or logarithmic). The purpose of this is to establish whether the most effective strategy to bridge the gap is through direct policy action and incentives, or a combination of direct policy action and incentives with a new strategy to promote consumption reduction.

The likelihood and scale of required consumption reduction is estimated for each of the sectors by outlining the general trend of material reduction needed to close the gap between the projected GHG emissions and the sector budget, once new policies and incentives have been deployed.

2.0

Methodology



2.1 GHG Emissions Budgeting

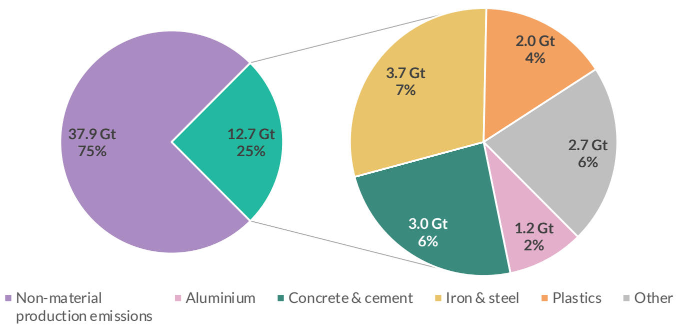
The concept of an GHG emissions budget was first introduced in the IPCC's Fifth Assessment Report (AR5) in 2014.[3] This moved the focus of the debate from climate change as a response to changes in atmospheric concentrations of GHGs, to focus on the impact of cumulative amounts of GHGs emitted by human activities. In 2021, the IPCC's Sixth Assessment Report (AR6) reaffirmed that there is a near-linear relationship between cumulative anthropogenic GHG emissions and global warming.[4]

Global GHG emissions in 2016 were estimated to be 47.4 Gt CO_2e, and grew by 3.2% to 48.9 Gt CO_2e in 2018.[5] Limiting warming to 1.5°C requires reaching net zero GHG emissions globally by at least 2050 and concurrent deep reductions in emissions of non-CO_2 forcers[ii], particularly methane.[6] In AR6, the IPCC provide a range of cumulative emission budgets based on the probability of limiting warming to 1.5°C. For the purposes of this study an emissions budget of **400 Gt CO_2e** has been chosen, which represents a **66% probability** of keeping global warming below 1.5°C. Given that at the current growth rates the cumulative budget of 400 Gt CO_2e will be exhausted by 2027, a reduction in annual GHG emissions is essential to limit warming and remain within the budget.

The material production sector is estimated to have emitted approximately 11 Gt CO_2e in 2011, which is around 25% of global GHG emissions.[7,8] Within material production, four sectors—**iron and steel; concrete and cement; aluminium; and plastics**—are estimated to account for 78% of emissions. Each of these sectors has been recognised by the World Bank's Mission Possible Partnership (MPP) as one of the seven 'hard-to-abate' sectors.[iii] These four key sectors are therefore the focus of the analysis in this report.

Based on historic growth in annual emissions, the global emissions in 2020 are estimated to be 50.5 Gt CO_2e and, therefore material production is estimated to account for 12.7 Gt CO_2e (Figure 2.1). Energy used in the production of materials is included within this sector. The other 37.9 Gt is emitted mostly through energy use in transport and buildings as well as food production.

Figure 2.1: GHG Emissions from Material Production in 2020[9]



For the purposes of this analysis, as materials production accounts for 25% of global CO_2e emissions currently, this sector is given a **cumulative emissions budget of 100 Gt CO_2e**. Each individual material is also allocated a budget based on their existing share. This is a simplified scenario and it is important to recognise that these budgets may vary with time, depending on the unique challenges each sector faces on the path towards net zero and their interconnectedness with the sectors emitting the other 75% of global emissions. This analysis attempts to lay the groundwork to help determine what the overall picture might look like where material use is optimised across all sectors in a coordinated way.

ii Non-CO_2 forcers are GHGs other than CO_2, such as methane, nitrous oxide and fluorinated gases, which trap heat within the atmosphere. These gases are emitted from a broad range of sectors and sources.

iii The other 'hard-to-abate' sectors are heavy-duty road transport, aviation and shipping – all transport related activities.

2.2 Sector Net Zero Strategies

Of the four industries in scope, the International Aluminium Institute (IAI) and the Global Cement and Concrete Association (GCCA) have produced net zero strategies. However, both the iron and steel and plastics industries are yet to publish a sector-wide net zero strategy. In the absence of this, scientific and grey literature has been used to inform possible pathways for each industry.

Based on the available net zero strategies and other scientific literature, the annual CO_2e emissions between 2020 and 2050 for each sector have been calculated.[iv] This is based on the estimated timing and uptake of introducing a technological intervention, and its maximum possible annual abatement potential (MPAP[v]). The baseline of the model assumes that the rate of adoption of a technological intervention will be exponential, with the sector-wide adoption rate growing from 1% in the year a technology was first commercially viable, to 100% after ten years. Linear and logarithmic adoption models were also investigated as a sensitivity. More detailed explanation of the three adoption models is provided in Appendix A.1.0.

Some of the key technological interventions, such as carbon capture, utilisation and storage (CCUS) and deployment of green hydrogen as a fuel source, are not yet proven at a commercially viable scale. To account for this, a risk rating is assigned to each technological intervention to account for the risk of its potential not being fully realised; each intervention is assigned a 'low', 'medium' or 'high' risk rating, which translates to a risk factor of 5%, 25% and 50% respectively. A technology that is considered 'high' risk would therefore see its effectiveness reduced by 50% when risk is accounted for in the modelling. Two values for cumulative emissions between 2020 and 2050 were calculated for each sector: one assumes that 100% of its potential will be realised, and another that accounts for the risk assigned to each intervention.

[iv] Although published in 2022, the model covers the period 2020 to 2050. Each BAU scenario reflects any improvements relating to emission reductions (such as electricity decarbonisation or increased recycling) that are believed to have occurred in 2021 and 2022.

[v] Maximum possible abatement potential refers to the theoretical maximum a technological intervention would be able to reduce CO_2e emissions in a given year.

3.0

Results

3.1 The Aluminium Sector

The International Aluminium Institute (IAI) has published a document entitled *Aluminium Sector Greenhouse Gas Pathways* to 2050, which outlines the projected business-as-usual (BAU) emissions in 2050 and proposes three interventions that will enable aluminium to become (almost) net zero in 2050. The IAI estimate that in 2018 the production of 95 million tonnes (Mt) of aluminium globally was responsible for 1.1 Gt CO_2e per annum. Therefore, the global carbon intensity of production of aluminium in 2018 was 11.5 t CO_2e produced per tonne of aluminium; however, this figure will vary considerably on a regional basis.

Under their BAU scenario, the IAI suggest that demand for aluminium is expected to grow by 80% from 2018 levels to 2050, rising to 171 Mt.[vi] Under the BAU scenario, annual emissions in 2050 would equal 2.0 Gt CO_2e, and the cumulative GHG emissions are predicted to reach 48 Gt CO_2e in 2050.[vii] This emission rate would account for around half of the emissions budget allocated to the four materials focused on in this report, and 12%[viii] of the IPCC's global 400 Gt budget.

The three interventions outlined by the IAI as having the potential to delink growth in aluminium production and GHG emissions are:

- electricity decarbonisation;
- direct emissions reduction; and,
- recycling and resource efficiency.

Table 3.1 highlights the maximum possible abatement potential of each of these proposed interventions, as well as the level of risk assigned to each. The timing of each direct emission reduction intervention is guided by the World Economic Forum's Mission Possible Partnership.[10] Using these timings, the annual emissions of aluminium production are calculated for each year between 2020 and 2050. Figure 3.1 illustrates that cumulative emissions are modelled to reach 18 Gt CO_2e by 2050 – close to double the 9.3 Gt budget.

Given that more than 50% of the direct emissions reduction is achieved through 'high' risk technologies (CCUS and green hydrogen), this is reflected in the modelling. When risk is accounted for, the cumulative emissions of the aluminium sector would equal 20 Gt CO_2e in 2050.

Table 3.1: MPAP for each Intervention in the Aluminium Sector

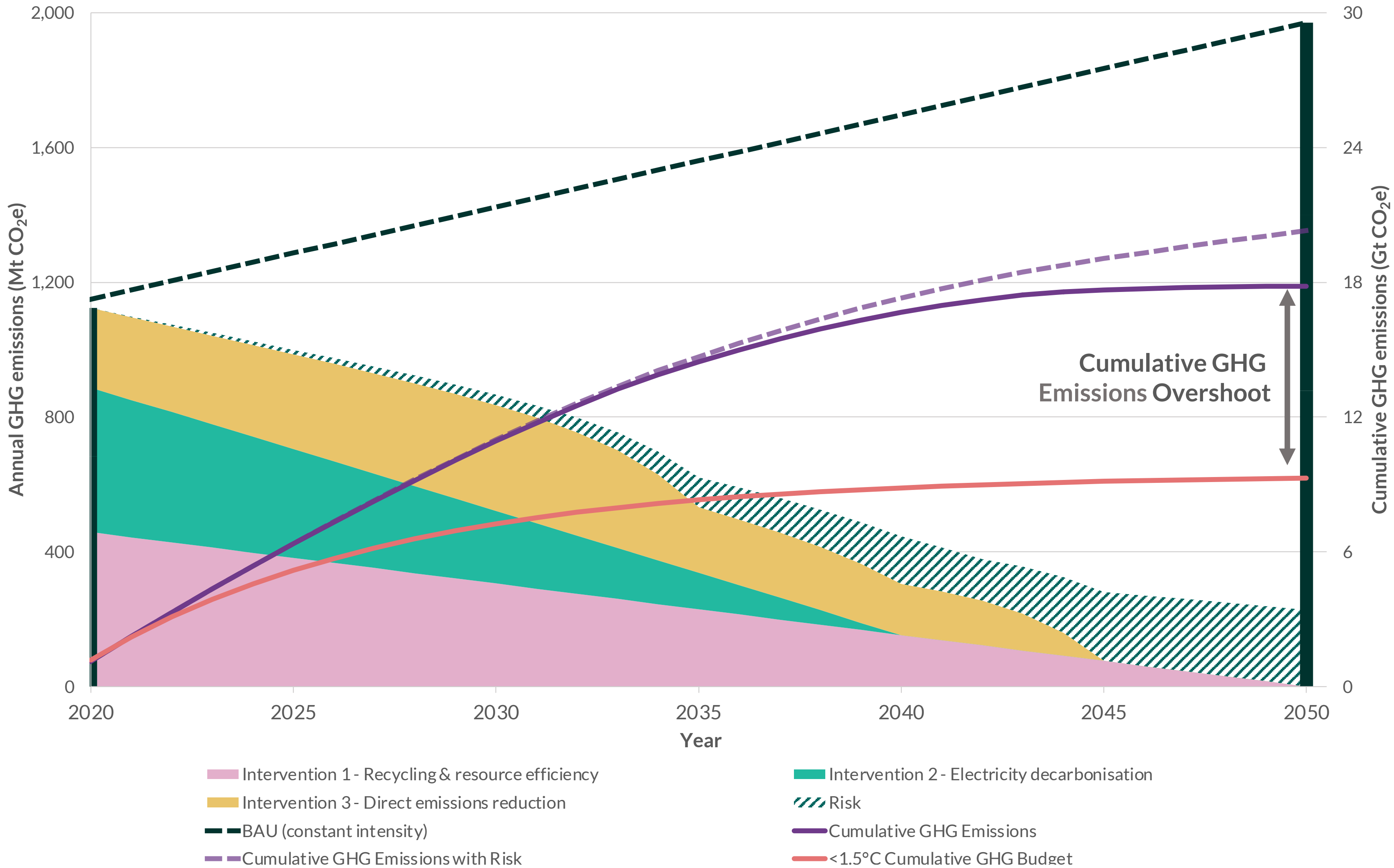
Technology	Year of Initial Deployment	2050 Abatement Potential (Gt CO_2e/ year)	Risk Level
Electricity decarbonisation			
Electricity decarbonisation	2020	0.88	Low
Direct emissions reduction			
Inert anode technology	2025	0.15	Medium
Mechanical vapour recompression	2025	0.10	Medium
CCUS	2030	0.07	High
Green Hydrogen	2035	0.21	High
Recycling and resource efficiency			
Increasing Recycling	2020	0.57	Low

vi This growth is expected to be met by a combination of secondary—up to 60% across the sector in 2050—and primary aluminium.

vii Note: the report recognises this pathway is expressed as CO_2e emissions, however, it also recognises that most emissions relate specifically to CO_2. It was, therefore, not deemed necessary to adjust the data to account only for CO_2.

viii This should be around 2% based on the relative contribution from the aluminium sector in 2018.

Figure 3.1: Modelling GHG Emissions for the Aluminium Sector – Expected Deployment Scenario



3.1.1 Accelerating Aluminium Decarbonisation

Given that the cumulative emissions exceed the aluminium-specific budget by 9 Gt CO_2e, there is a clear need for a concerted effort to accelerate the development and deployment of the technological interventions listed in Table 3.1.

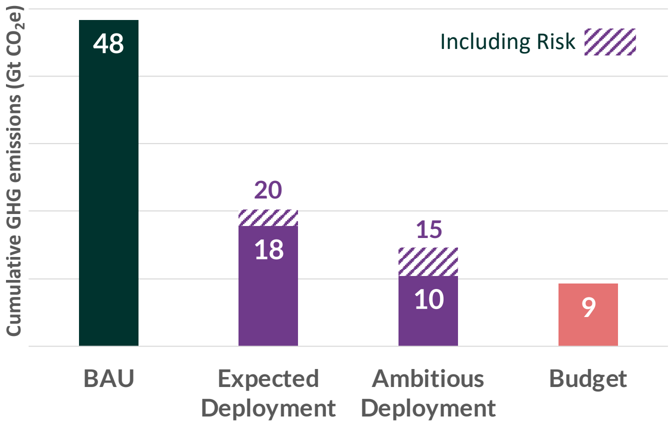
Electricity-related GHG emissions dominate the emissions of the sector, accounting for almost 65%, with 95% of this associated with the smelting process. As such, the greatest potential for reduction is likely to stem from the rate at which electricity decarbonisation of the smelting process is achieved. Whilst the assumption is that there will be a linear decarbonisation of electricity between 2020 and 2040, the annual GHG emissions of aluminium production could be substantially reduced if 100% renewable electricity is achieved prior to this. In a scenario where the electricity used in aluminium production is net zero-carbon by 2030, the cumulative emissions would be greater than 15 Gt CO_2e – a 14% reduction compared with the expected deployment scenario, but still exceeding the budget by 6 Gt (66%).

Although it is clear substantial reductions in cumulative emissions can be realised through electricity decarbonisation, there are some potential barriers to accelerated deployment. Historically, the global smelting electricity mix was dominated by hydropower,[11] but is now increasingly fuelled by coal and gas combustion[ix] due to the growth of smelting capacity in China and other parts of Asia which predominantly use fossil fuels.[x] Though several aluminium producers have stated plans to increase hydropower-based production (which is not without its own ecological problems) and/or relocate to areas with renewable energy production, much of the coal-fired capacity is relatively young, with assets fewer than 10 years old[12] – therefore without specific intervention, coal-fired production is likely to remain into the coming decades.

In addition, two-thirds of electricity required in the aluminium sector is generated in on-site plants specifically to feed the smelter. As such, the commitments made by several nation states to achieve zero carbon national electricity grids by 2035[13] will not always include or directly benefit the aluminium sector. As a result, significant capital investment is needed to achieve electricity decarbonisation.

If more ambitious (but feasible) deployment targets are achieved (outlined in Appendix A.2.1) compared with current commitments, the aluminium sector would be able to limit their cumulative emissions to 10 Gt CO_2e by 2050; though still exceeding the budget by 13% (Figure 3.2).

Figure 3.2: Aluminium Decarbonisation Scenarios



This scenario illustrates that even with the extremely rapid adoption of technologies, their associated risks mean that further action will be required for the sector to remain within the sector-specific budget.

To avoid the GHG emissions overshoot, the increase in the demand for virgin aluminium would need to slow and even reverse from current levels. In order to meet the budget it is highly likely that global per capita consumption of aluminium must fall rather than grow over the long term. Any delay in this will make it increasingly more difficult to remain within the allotted budget, and the required consumption reduction would need to be greater to compensate. For example, maintaining per capita demand at 2020 levels is likely to keep within the budget under the ambitious deployment scenario, but if demand continues to increase beyond 2025, a real terms decrease of ~30% per capita will be needed soon thereafter. The longer that annual consumption increases, the more reduction will be needed subsequently to remain within the budget.

[ix] This is due to growth of smelting capacity in regions reliant on fossil fuels, e.g., in 2018, 75% of power for smelting was via hydropower in Europe, while 89% of power for smelting was from coal combustion in China. In 2018 Europe was responsible 12% of production and China 57%.

[x] In 2018, although 75% of power generated for smelting was via hydropower in Europe, Europe was responsible for only 12% of production. Conversely, 89% of power generated for smelting was from coal combustion in China in 2018, which accounted for 57% of production.

3.2 The Cement & Concrete Sector

The Global Cement and Concrete Association (GCCA) has published a net zero roadmap which outlines the BAU emissions in 2050, and proposes seven interventions to achieve net zero in 2050. Under their BAU scenario, the GCCA projects that demand and the associated annual GHG emissions will rise by 42% from 2020 to 2050. Their estimate assumes no change in current practices with the carbon intensity of production remaining at 0.64 t CO_2e per tonne of concrete and cement produced. Under this scenario, the sectoral cumulative emissions would total 101 Gt CO_2e by 2050, accounting for a quarter of the IPCC's 400 Gt global budget and the entire budget allocated to all material production.[xi]

The seven interventions outlined by the GCCA to delink growth from emissions have been categorized as:

- CCUS;
- electricity decarbonisation;
- multiple improvements in production efficiency; and,
- recarbonation.[xii]

Table 3.2 highlights the MPAP of each of these interventions, as well as the level of risk assigned to each. Using the timings outlined by the GCCA, the annual GHG emissions of cement and concrete production are calculated for each year between 2020 and 2050. Figure 3.3 illustrates that the annual emissions from cement and concrete production are modelled to reach zero by 2050. However, the cumulative emissions (45Gt CO_2e) exceeds the sector specific budget by 88%. In addition, due to the sector's reliance on technological interventions with high risk, such as CCUS, this overshoot is further increased to 38 Gt (158%) in excess, when accounting for risk.

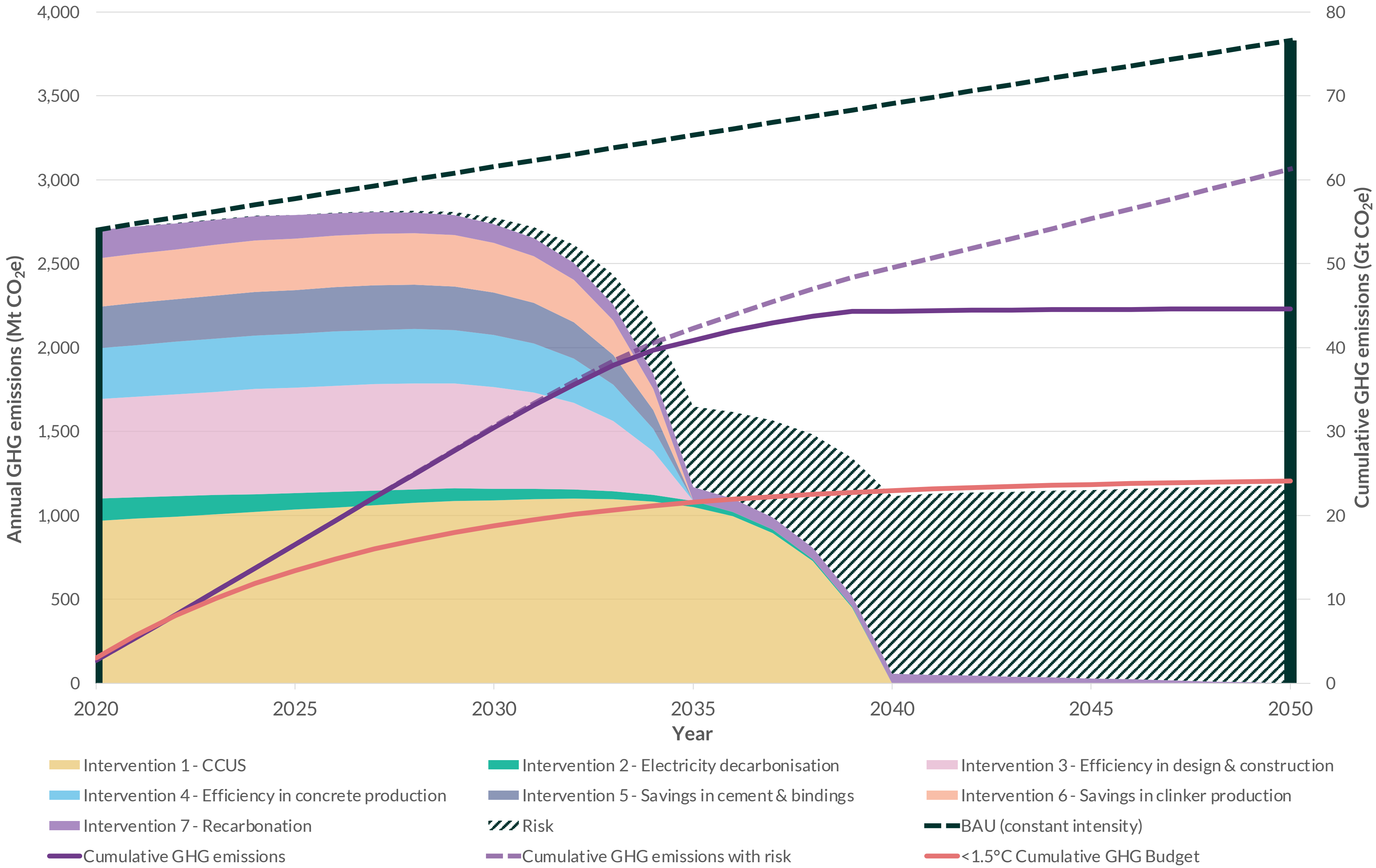
Table 3.2: MPAP for each Intervention in the Cement & Concrete Sector

Technology	Year of Initial Deployment	2050 Abatement Potential (Gt CO_2e/ year)	Risk Level
CCUS	2030	1.37	High
Electricity decarbonisation	2020	0.19	Low
Recarbonation	2020	0.24	Low
Improvements in production efficiency			
Design and construction	2020	0.84	Medium
Concrete production	2025	0.43	Medium
Cement and binders	2025	0.35	Medium
Clinker production	2025	0.41	Medium

[xi] It is recognised that most of the cement and concrete sector's direct emissions are CO_2, as opposed to other greenhouse gases, so decarbonisation in the context of this strategy refers to CO_2 mitigation.

[xii] Recarbonation is the reabsorption of carbon dioxide from the atmosphere, which mineralises the concrete and enhances its stone-like properties.

Figure 3.3: Modelling GHG Emissions for the Cement & Concrete Sector - Expected Deployment Scenario



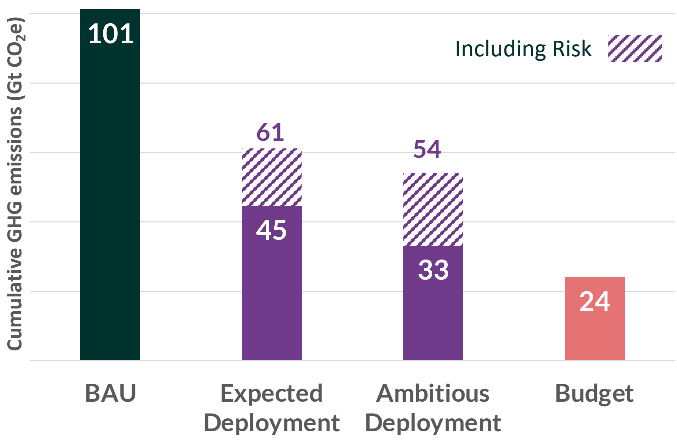
3.2.1 Accelerating Cement and Concrete Decarbonisation

In this industry's decarbonisation trajectory, electricity decarbonisation is only responsible for 5% of sectoral emissions. As a result, advancing the year at which the grid carbon emissions reach zero has relatively little impact on cumulative emissions. It is CCUS that is expected to have the greatest abatement potential in this industry, with the GCCA estimating that 1.4 Gt CO_2e will be annually abated via CCUS by 2050. The GCCA's Roadmap also recognises that the contribution from CCUS will only become significant after 2030, when commercial viability and necessary infrastructure is projected to be established; yet the plan states that they aim to have proven carbon capture technology at an industrial scale at 10 plants by 2030.[xiii] Therefore, to test the sensitivity of initial implementation on cumulative emissions, the date of implementation of CCUS has been brought forward to 2025 in the model.

Furthermore, improvements in the design and construction of buildings have been introduced in the model from 2022 as many practises covered by this intervention, such as design optimisation and revised building specifications, are beginning to be implemented.[xiv] The remaining technologies are also introduced in 2022. The exact timings of implementation of these technological interventions are outlined in Appendix A.2.2.

CCUS is expected to have the greatest abatement potential.

Figure 3.4: Cement Decarbonisation Scenarios



Under this very ambitious scenario, the cumulative emissions total is still estimated to be 38% more than the sector-specific budget in 2050 (Figure 3.4). This suggests that a reduction in the consumption of cement and concrete is needed to sufficiently reduce cumulative emissions from this sector. Under the ambitious deployment scenario, consumption would need to reduce from 4.2 Gt to 2.15 Gt by 2030, then fall further by 2050. This would result in a significant reduction in per capita consumption (up to 50% by 2030) of concrete and cement. Preventing the need for such aggressive consumption reduction can only be achieved by a similarly aggressive adoption of technological interventions with a linear rate of adoption. With this, cumulative emissions would equal 25 Gt CO_2e – allowing the sector to exceed its specific budget by 1 Gt (Figure A2-2-1). This not only demonstrates the high level of uncertainty associated with modelling the industry's future, but also re-enforces the underlying conclusion to rapidly adopt technological interventions over the coming years.

xiii According to the Global CCS Institute, of the 28 operational carbon capture plants none are currently linked to cement and concrete production.

xiv The GCCA's roadmap highlights the need for support of built environment stakeholders, including architects, engineers, and the full value chain.

3.3 The Iron & Steel Sector

In conjunction with the industry members of the Net-Zero Steel Initiative, the MPP have published a Net zero steel: sector transition strategy, which outlines several pathways to achieve net zero steel.[14] Under their BAU scenario, the MPP project that the annual demand for iron and steel will increase by one third to 2.6 Gt by 2050. As a result, the sectoral GHG emissions are projected to increase from 2.6 Gt CO2e in 2020 to approximately 3.5 Gt CO_2e by 2050, with cumulative emissions over the three decades totalling 94 Gt CO_2e.[xv]

The MPP and the International Energy Agency (IEA)[15] have outlined several areas that have the potential to meet the demand for iron and steel, whilst also reducing GHG emissions associated with production:

- improved recycling and use of electric arc furnaces (EAF) with decarbonised electricity;
- green hydrogen, and;
- implementation of CCUS.

Table 3.3 highlights the MPAP of each of the suggested interventions.

Table 3.3: MPAP for each Intervention in the Iron and Steel Sector

Technology	Year of Initial Deployment	2050 Abatement Potential (Gt CO_2e/ year)	Risk Level
Recycling with EAF	2020	1.7	Low
Green Hydrogen	2030	1.2	High
CCUS	2020	0.6	High

In the MPAP scenario, 70% of the iron and steel demand is expected to be met from scrap recycling by 2050; an increase from 30% in 2020. This secondary (scrap-based) production is less carbon-intensive than primary production as electricity, rather than direct combustion of fossil fuels, can be used to melt scrap. Although it is highly dependent on the carbon intensity of the electricity supply, GHG emission are substantially lower than traditional Blast Furnace-Blast Oxygen Furnace (BF-BOF) production methods.[xvi]

The IEA highlights that innovations such as the green hydrogen-based direct reduced iron method (replacing coking coal in blast furnaces) and the implementation of CCUS will need to reach market readiness and start being deployed by 2030.[xvii] The adoption of these technologies will need to be widespread. For example, in the MPP's net zero scenarios, steel produced using 100% low-carbon hydrogen[xviii] will account for 40%–55% of primary steel production in 2050. Rapid scaling of CCUS capacity is therefore also needed to facilitate the transition to net zero.[16] Of the 26 commercial carbon capture facilities in operation globally, only one has been developed at an iron and steel plant.[17]

Using these assumptions, the annual GHG emissions of iron and steel production are calculated for each year between 2020 and 2050. Annual GHG emissions are assumed to fall to zero by 2050 which results in cumulative emissions totalling 46 Gt CO_2e (Figure 3.5). This is 16 Gt (55%) more than the sector-specific budget. The cumulative emissions are further increased when accounting for risk, generating cumulative emissions that are 36 Gt (123%) more than the budget. The substantial rise in the cumulative emissions is due to the 'High' risk technological interventions of CCUS and green hydrogen-based production.[xix]

[xv] The Mission Possible Partnership states that the majority of the steel sector's direct emissions are CO_2, as opposed to other greenhouse gases, so decarbonisation in the context of this strategy refers to CO_2 mitigation.

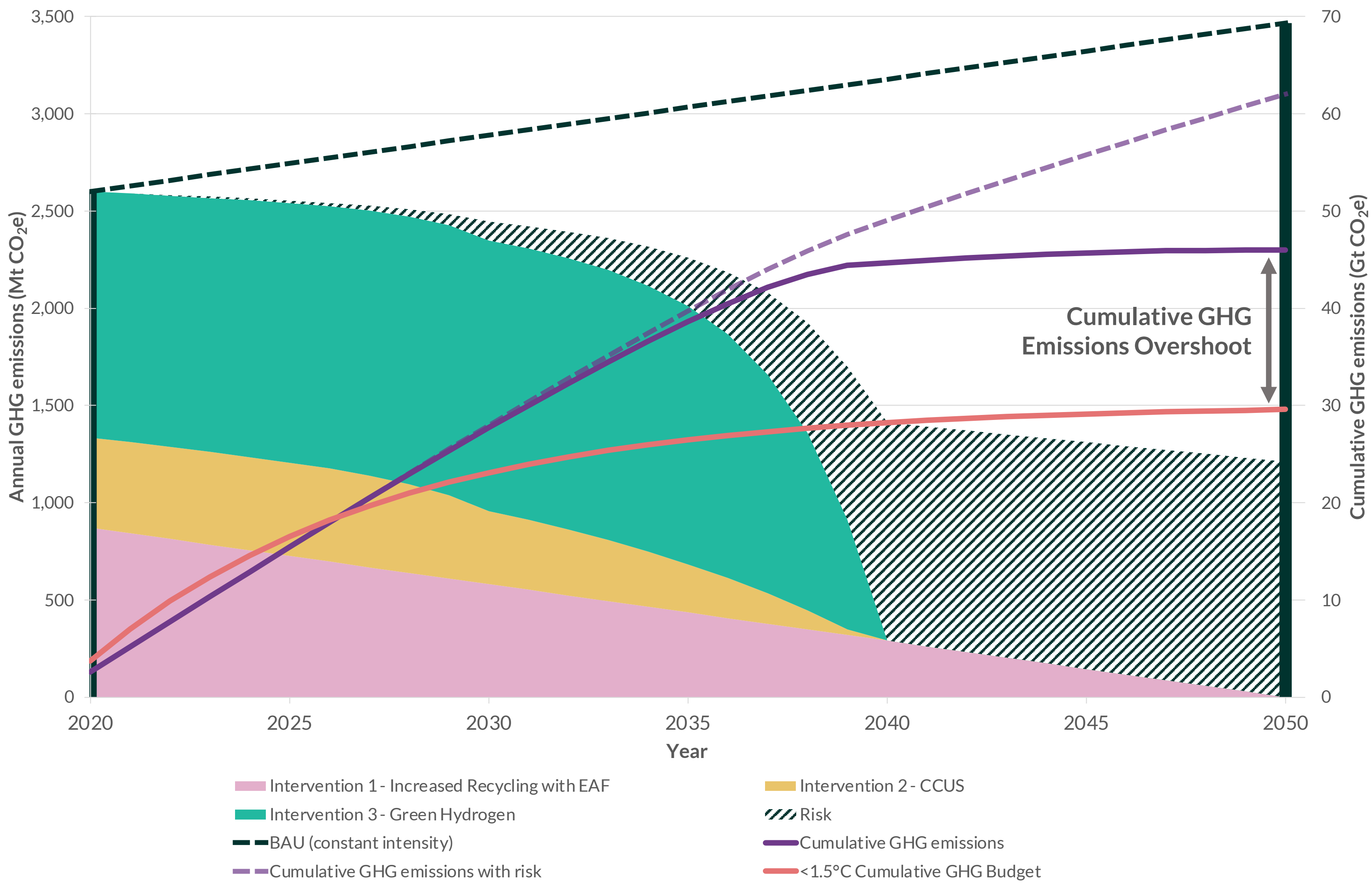
[xvi] Although dependent on the carbon intensity of the electricity supply, emissions from steel produced via EAFs currently have average emissions of 0.6 tCO_2/t, compared to 2.3 tCO_2/t from traditional BF-BOF production.

[xvii] The MPP suggest the 10 (near-) zero-emissions technology archetypes are based on zero-carbon electricity, zero-carbon hydrogen, or carbon capture.

[xviii] Low-carbon (green) hydrogen is generated by renewable energy or from low-carbon power. It has significantly lower carbon emissions than blue hydrogen – produced by steam reforming of natural gas.

[xix] The MPP suggests ~0.3 Gt of residual GHG emissions from the sector will remain in 2050, primarily due to expected leakage from CCUS (90% effective capture rate) and electrode degradation in EAFs.

Figure 3.5: Modelling GHG Emissions for the Iron & Steel Sector - Expected Deployment Scenario



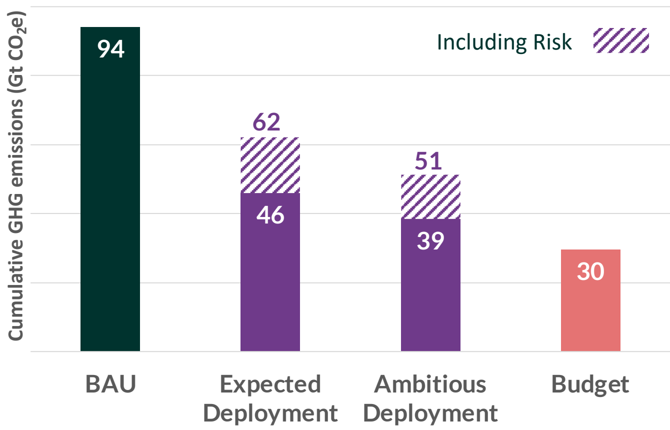
3.3.1 Accelerating Iron & Steel Decarbonisation

Given that under the existing net-zero pathway for the iron and steel sector the cumulative emissions exceed the industry's specific budget by 16 Gt CO_2e, there is a need for concerted efforts to accelerate the development and deployment of the technological interventions listed in Table 3.3.

The IEA highlight several innovative production methods, with several research and development projects underway around the world that may facilitate the interventions: for example, the HYBRIT project in Sweden is developing hydrogen-based Direct Reduced Iron (DRI) production due to come online as early as 2026.[xx] If the project is successful, then full commercialisation of similar technological interventions could occur in the following decade. However, another study suggests that retrofitting existing systems with best available efficiency technologies will provide the greatest abatement potential and could be implemented immediately.[18]

A significant change is likely to be required within the sector to sufficiently limit cumulative emissions.

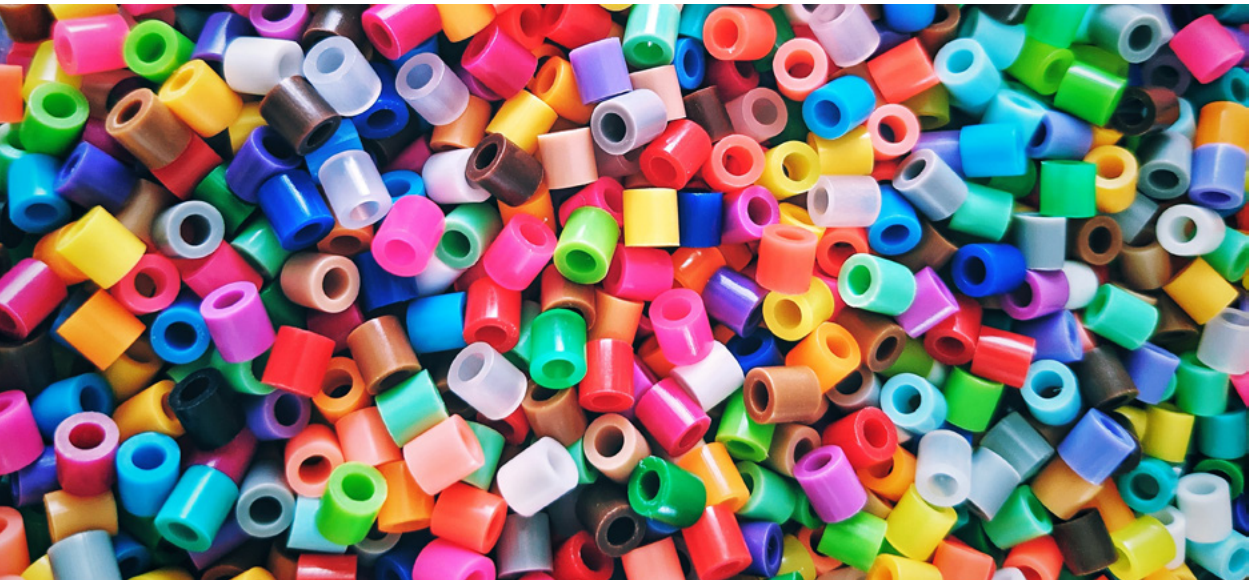
Figure 3.6: Iron & Steel Decarbonisation Scenarios



The level of risk associated with retrofitting is much reduced and would fall into the 'Medium' category. It could also be brought forward five years to be implemented from 2025 onwards. With this approach as part of an ambitious deployment scenario (Appendix A.2.3), the cumulative emissions in 2050 could be reduced further to 39 Gt CO_2e, although this is still 30% more than budget (Figure 3.6).

As such, a significant change is likely to be required within the sector—such as reduction in consumption—to sufficiently limit cumulative emissions. Based on the scenarios modelled from the available date, per capita consumption may need to fall below current levels by 50% from 250 kg per capita per year, down to 125 kg per capita by 2035. These results are highly sensitive to both the rate of reduction and the adoption of technologies but demonstrate that current consumption levels are unlikely to be sustainable.

[xx] Direct reduction involves reducing iron oxides to metallic iron at temperatures below the melting point of iron. This is often achieved by using a reducing gas (typically a blend of hydrogen and carbon monoxide derived from natural gas).



3.4 The Plastics Sector

In the absence of a sector-wide net zero pathway for the plastics sector, academic literature was used to inform the modelling of the BAU scenario and net-zero pathway. Previous research (e.g., Zheng & Suh, 2019[19]) calculated that the production of 0.41 Gt of fossil-based plastics in 2015 emitted 1.8 Gt CO_2e over their lifecycle. The BAU scenario assumes that the significant growth in all global plastic production witnessed historically is likely to continue at an annual growth rate of 4%, reaching 1.6 Gt annually by 2050.[20,21] With no change from current practices, total annual GHG emissions in 2050 are estimated to reach 7 Gt CO_2e, with cumulative emissions reaching 129 Gt CO_2e[xxi]. This is greater than the budget for all material production, and 32% of the IPCC's entire budget for limiting warming to 1.5°C.

There is a fundamental barrier in reducing GHG emissions associated with fossil-based plastics, given that the material is built out of carbon and therefore preventing its release is imperative.[22] However, it has also been stated that by combining a range of circular technologies, net zero emission plastics could be achieved[23] - it is the timing of the deployment of these technologies that will be critical for staying within the budget. The available literature outlines four interventions to decarbonise plastics throughout their lifecycle:

- the improvement of energy efficiency and decarbonisation of production;
- the increase in global recycling rate from 15% to 60%;[xxii]
- a partial (~50%) switch to bio-based feedstock principally from sugar cane/beet; and,
- CCUS technology applied at all parts of the value chain, including petroleum refining, steam cracking, and waste incineration.

Table 3.4 shows the estimates of the decarbonisation potential for each of the proposed interventions, as well as the level of risk assigned. Using the timings of these interventions, the annual GHG emissions of plastic production were calculated for each year between 2020 and 2050. As shown in Figure 3.7, the annual GHG emissions from the plastic production sector are modelled to reduce to zero in 2050. In reality, there is large uncertainty around how this may be achieved, particularly if fossil-based plastic still plays a significant role. The oil and gas extraction industry extraction emissions—particularly fugitive emissions—cannot easily be abated and may also be significantly underestimated in current inventories.[24]

Under the modelled scenario (Figure 3.7), the sector-specific budget of 16 Gt is exceeded by three times over. In addition, due to the sector's likely reliance on technological interventions with a higher risk to abate remaining emissions (such as CCUS[xxiii]), this overshoot is increased further when accounting for this risk – with cumulative emissions totalling four times the budget.

Table 3.4: MPAP for each Intervention in the Plastics Sector

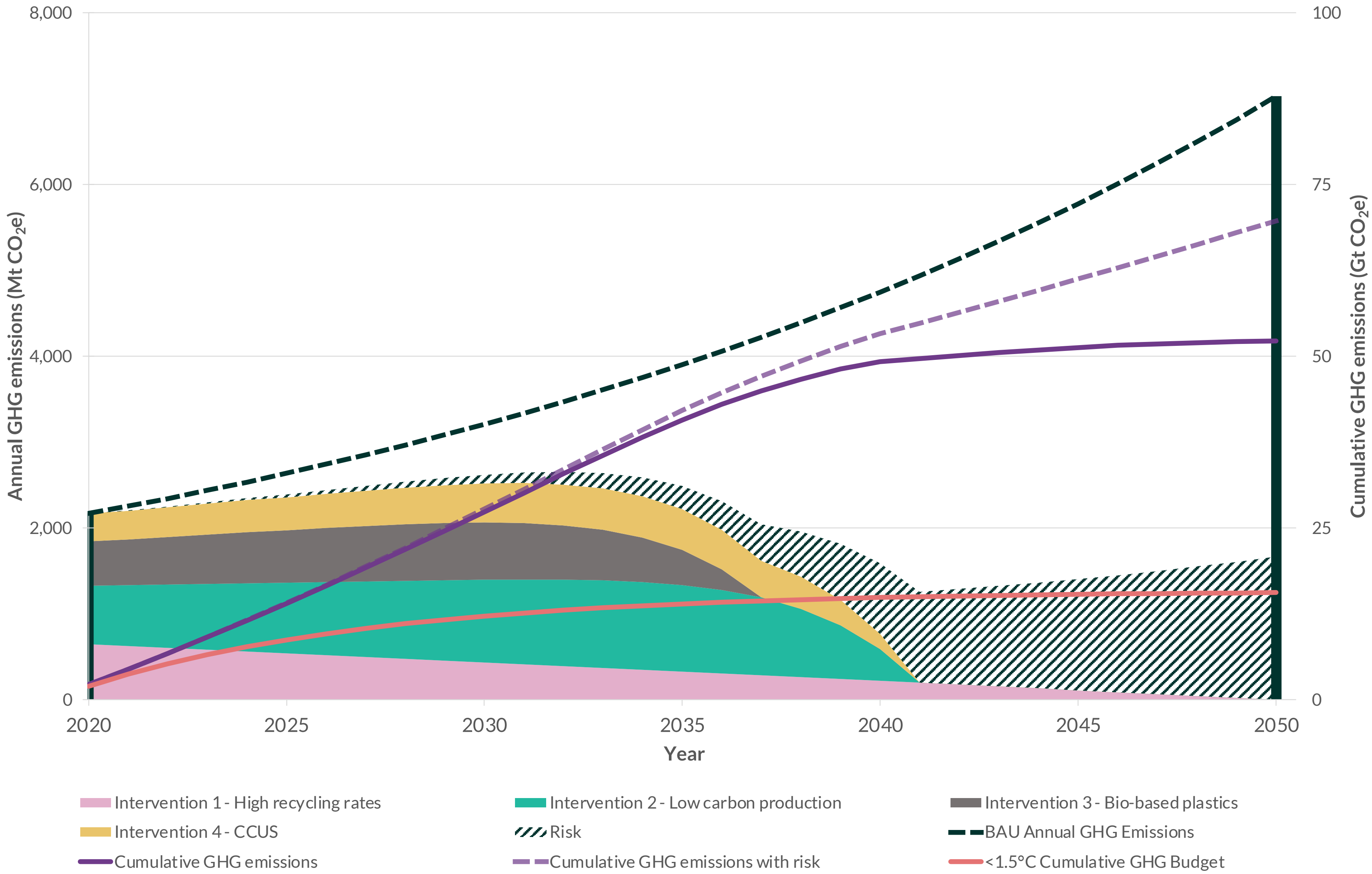
Technology	Year of Initial Deployment	2050 Abatement Potential (Gt CO_2e/ year)	Risk Level
Low carbon production	2025	2.2	Medium
High recycling rates	2020	2.1	Medium
Bio-based plastics	2020	1.6	Low
CCUS	2025	1.0	High

xxi Note: the report recognises that emissions are expressed as CO2e. However, in the absence of a sectoral pathway, and further data, it was not possible to adjust the data to reflect only CO_2.

xxii In this scenario, end-of-life treatment sees 60% of plastic waste recycled, 28% sent to landfill and the 12% balance being incinerated. Current split is 15% recycled, 58% landfill and 24% incineration as estimated in Zheng & Suh (2019) – the ceiling for recycling rate is likely to be lower than other materials due to losses in the process.

xxiii CCUS works best with a single, large-scale emissions source, with a high CO_2 concentration. However, there are three separate emissions sources in plastic production (petroleum refining, steam cracking, and waste incineration) all at different steps in the value chain, thereby limiting the potential of CCUS.

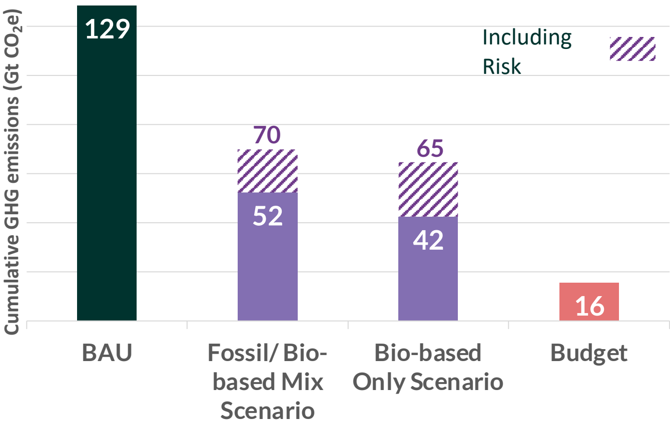
Figure 3.7: Modelled GHG Emissions Pathway for the Plastics Sector - Fossil/Bio-based Mix Scenario



3.4.1 Accelerating Plastics Decarbonisation

Remaining within the plastic specific budget will be a significant challenge for the plastics industry. Most notably, it is the only one of the industries in this study that is expected to fundamentally shift towards a totally different raw feedstock for virgin production. A further scenario whereby the plastics industry shifts to 100% bio-based feedstocks finds that the budget is still exceeded by almost three times – the risk factor is increased due to the current lack of bio-based alternatives for many of the common polymers on the market currently (Figure 3.8).

Figure 3.8: Plastics Decarbonisation Scenarios



Remaining within the plastic specific budget will be a significant challenge for the plastics industry.

This exceedance occurs despite the transition being modelled to be complete by around 2037 – a much more aggressive shift than is currently expected given the lack of policy intervention in this area. Moreover, modelling of a transition to bio-based plastics and the impacts it will have is a challenging process and highly uncertain at this time. There are many complex and interconnected aspects which are subject to change such as:

- the exact mix of bio-based feedstock (e.g. sugar, corn algae etc.);
- whether substantial amounts of feedstock can come from waste;
- how changes in land-use impact carbon release and sequestration (and the interplay between other uses of land for food; materials and fuels), and;
- the methodological issues around accounting for biogenic carbon and its sequestration in products over short and long timeframes.

These issues may all contribute to slowing down any transition towards bio-based plastics, as evidence for the best pathways is gathered and assessed.

A similar challenge is also present for recycling – once again plastics are unique in this aspect. For example, the role of chemical recycling technologies may become prominent over the next decade in response to drive for ambitious recycling and recycled content targets. However, the net zero pathway for these processes and the legacy of the petrochemicals industry surrounding it is extremely unclear.

Even given all these uncertainties, the modelling suggests that plastic consumption will need to be reduced to limit cumulative emissions even if concerted action takes place. The scenarios in this study suggest that to come close to the budget, rather than growing by 4% annually, the demand for plastics would need to reduce by 3% each year whereby the annual consumption would be halved by 2050 which would result in a per capita consumption reduction of around 75%.

4.0

Discussion & Recommendations

The analysis of each sectors' decarbonisation strategies has demonstrated that at their expected pace of deployment, the intended interventions are inadequate to limit GHG emissions to within a carbon budget that will help to limit global warming to 1.5°C. As shown in Figure 4.1, under the current trajectories, GHG emissions continue to rise sharply until 2040 and cumulative emissions in 2050 are in excess of 160 Gt CO_2e—over double the 78 Gt budget allocated to the specific industries analysed in this study, with the cumulative budget exceeded before the end of this decade. When accounting for risk associated with the technological interventions, the cumulative emissions is 220 Gt CO_2e, almost three times the budget.

Taking a BAU approach to materials production will lead to exceeding the budget by almost five times and result in a trajectory of warming towards 2.5°C. For the plastics industry alone, this is as high as 3.5°C. Current industry net zero roadmaps bring the difference to double the budget and a warming of around 1.7°C – although with technological risk factored in, this could be as high as 2°C. The plastics industry currently does not have a roadmap to net zero, but projections for this study suggest that a trajectory of 2.2°C is possible even with aggressive decarbonisation.

If the other ~75% of the global GHG emissions from non-material sectors (primarily from energy) can remain within budget, the material sector alone would be responsible for reaching 1.6°C under the expected deployment scenario.

Figure 4.1 also highlights the need to deploy technological interventions as soon as possible. However, not only does the deployment of these technologies need to be significantly advanced in the coming years, the rate at which each of the sectors adopts these interventions will also need to accelerate.

Furthermore, whilst this report has taken the scenario of 67% chance of keeping to 1.5°C, to increase the chances of limiting warming to 1.5°C, cumulative emissions must be minimised even further. The IPCC estimate that if cumulative emissions are kept below 300 Gt, there is an 83% chance of limiting warming to 1.5°C. In such a scenario, the emissions budget for the four sectors would be 59 Gt CO_2 which would be exceeded by 2026, and by 2050 the cumulative emissions would be 100 Gt greater than the budget.

As shown in Figure 4.2, under the expected deployment scenario, the importance of interventions is generally evenly split between recycling, energy, and improvements in production efficiencies. Aluminium has the most reliance on energy decarbonisation and cement has the most reliance on CCUS. It is interesting to note that whilst material recycling plays a key role in reducing virgin material demand, it will only partially counteract the expected growth in demand for most industries (with the exception of cement). Therefore, high recycling rates are only one facet of an effective decarbonisation strategy. The limitations of recycling are quickly reached and a shift from material circularity to product circularity is likely to be the only way this can be improved further.

Under the accelerated adoption scenario the cumulative GHG emission budget in 2050 is still exceeded for each of the materials (Figure 4 3). A real reduction in material consumption within each sector, or a significant shift in material consumption to less carbon-intensive sectors, is therefore critical to bridging that gap. For materials such as aluminium and steel that gap is smaller and involves lower risk technologies. For cement and, in particular, plastics, more drastic action may be required.

Future Policy

The main conclusion of this study is that **net zero by 2050 plans in the materials sector are unlikely to be enough to limit warming to 1.5°C**, and likely trajectories show the result could be as high as 2°C.

The modelling illustrates that there are key parameters that influence the cumulative GHG emissions from the relevant industries. These include:

- The year of initial deployment of technological interventions, and
- The growth model adopted to implement the interventions for each industry

Policy mechanisms are therefore required to promote the implementation of sector-specific measures to accelerate reductions in GHG emissions. Key to this is the recognition that **net zero should be replaced with 1.5°C aligned carbon budgets and supporting consumption based targets**. Priority should be given to accelerating the identified reduction pathways and providing a policy environment in which these technological interventions are deployed rapidly and effectively. This research highlights the importance of the timeline of implementation; more specifically, **the impact of deploying technologies after 2030 is substantially less effective than more near-term, widespread, commercial deployment**. One of the most pressing policy mechanisms to be devised is, therefore, to encourage rapid, near-term investment by industry to adjust their current projected timelines. This means that alongside the drive for increasing circularity, reducing primary GHG emissions should also be a priority as well.

Figure 4.1: Cumulative Material GHG Emissions - Expected Deployment Scenario

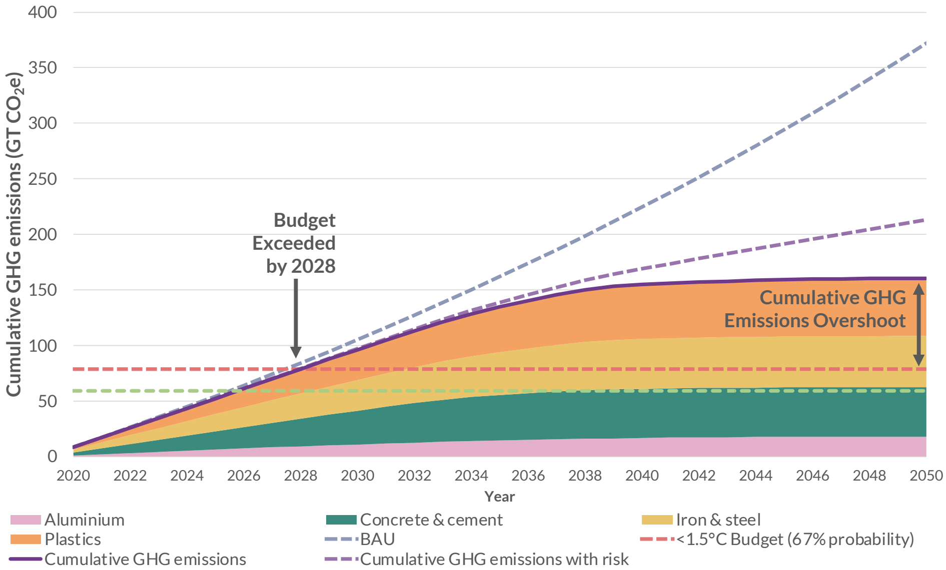


Figure 4.2: Reduction in Cumulative Emissions by Intervention Category – Expected Deployment Scenario

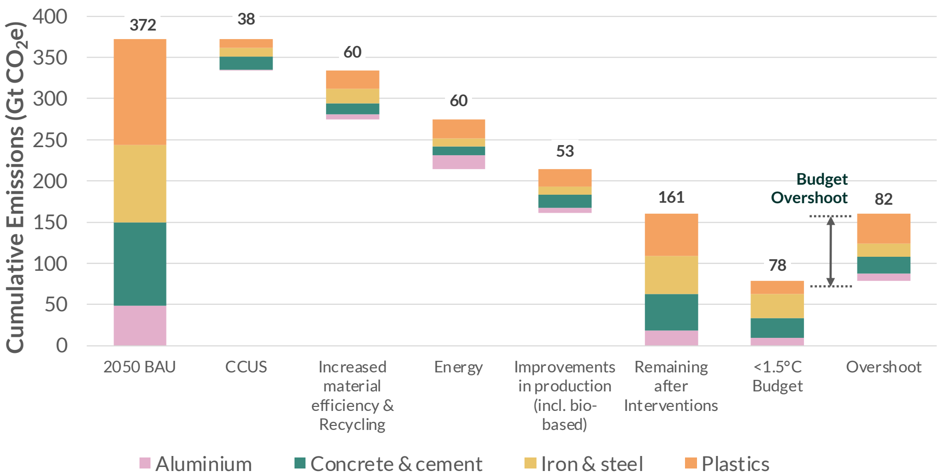
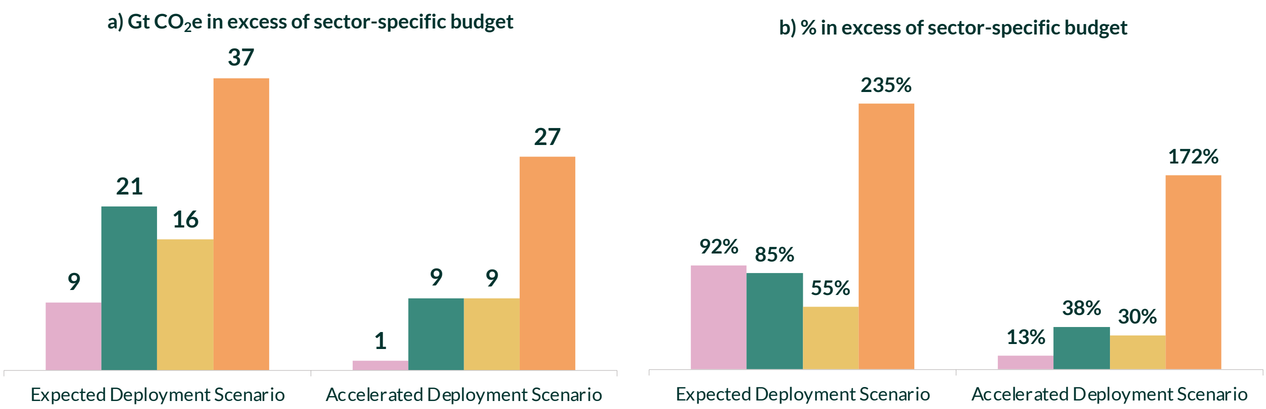


Figure 4.3: Sectoral Comparison of a) Gt CO_2e and b) Percentage more than their Sector-Specific Budgets



Rapid, near-term investment will not be without its challenges – the investment cycle of various plants and equipment within each industry can be significant. It must therefore be carefully considered how relatively new, high-emission plants will be incentivised to deploy new interventions.

Furthermore, the policies must:

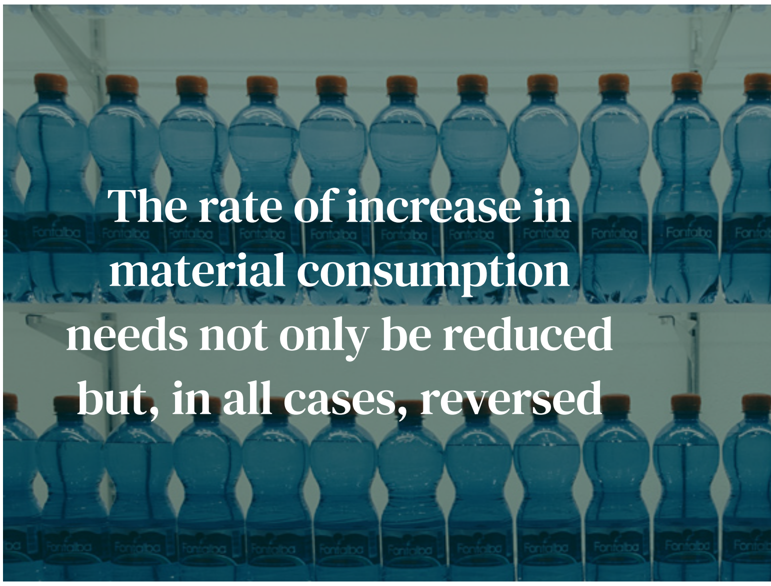
- secure long-term access to competitively priced renewable electricity;
- promote energy storage to stabilise renewable energy supplies; and
- drive increased investment in research, development and deployment of electrified processes, green hydrogen, and CCUS.

The above should be accompanied by continued investment in the decarbonisation of the energy grid. Renewables are now the cheapest form of energy and provide social and economic benefits, as well as environmental. The EU has committed to decarbonising the energy grid but new policies and incentives are required to aid industry to decarbonise, as many industries in the materials sector require purpose-built electricity generation and supply systems.

However, these policies only serve to amend the current business model of continued material production, which the modelling demonstrates is likely to be inherently unsustainable. Therefore, policies need to be supplemented to reduce the risk of under-delivering on GHG emission reductions, improve the likelihood of remaining within the carbon budget, and limiting global warming to within 1.5°C. Key policy interventions should therefore focus on measures that:

- reduce material consumption, and/or
- drive a shift in material consumption to less carbon-intensive sectors.

To further reduce the risk of overshooting the global carbon budget, **the rate of increase in material consumption needs not only be reduced but, in all cases, reversed**. The extent of this reversal is inextricably linked to the speed of decarbonisation. This requires new business models that decouple the use of material from the value it brings – answering the challenging question of how can businesses provide the same of improved level of service to a consumer, but with less material?



High recycling rates and circularity at the material level has its limitations – when *material circularity* reaches its limits, product *circularity* should be the focus which must also go beyond waste prevention as a metric for success. This will likely be in the form of greatly increased reuse, which is why **it is imperative that policies related to resource use are integrated with those on waste, recycling and product design.**

A change in business models will push industry to implement stronger circular economy principles, with virgin materials becoming less economical to purchase. This type of thinking is already being tested with the EU's Plastics Own Resource[25] where taxes are placed on virgin non-recycled plastics. However, more is needed for other materials and sectors, along with more interconnected policies linking resources and circularity.

Policy making should also deal with the concept of legacy emissions, and the global inequality in responsibility for depleting the carbon budget. Apportioning national or bloc-based carbon budgets (e.g., for the EEA) is one method to ensure the carbon overshoot does not occur. At present there is no consensus around how this may be done. Arguably the most equitable way is an even distribution across the globe of a per capita carbon budget. This would mean that it is likely that developing countries are likely to have room to increase consumption, but developed nations will have to decrease consumption at a much greater rate to compensate – whilst all nations focus on, and share technological developments in, decarbonisation.

This approach is aligned with the principle of ‘common but differentiated responsibilities’ and respective capabilities introduced by the UN, which recognises the need for all states to take responsibility for global environmental problems whilst also recognising the differences in economic development between states.

Finally, some consideration also needs to be given to whether material switching between industries is a valid approach, and how this can be (and whether it should be) driven at a macro level rather than relying on businesses to make individual micro decisions based on variable evidence. It is clear that materials industries face differing challenges that have varying levels of risk, and therefore it could be argued that moving towards materials with low-risk decarbonisation strategies may help keep the materials sector as a whole within the budget. For example, whilst cement is a mainstay in buildings across the world, the switch to timber is an often-cited alternative that also has benefits in terms of long term carbon sequestration.[26] Similarly, plastics are often being replaced by paper products and it is clear that what remains must move towards bio-based feedstocks. Forestry products were not included in this study, but are the fifth largest materials source of GHG emissions – switching to these would undoubtedly make the sector more prominent and worthy of further study around decarbonisation pathways.

A theme therefore emerges of a move towards growing materials rather than extracting them – this means that, from a policy perspective, there will need to be an increasing overlap between material resources and the bioeconomy. Addressing one without consideration of the other will lead to unintentional trade-offs. Competition for land use in the future between resources for materials, fuels and food whilst focusing on habitat protections is a key issue that needs to be discussed holistically rather than compartmentalised. Policy makers need to be aware of these interlinkages when designing measures to accelerate the path to net zero.

Future research

This research aimed to provide some indicative scenarios around materials and their contribution towards a global carbon budget. However, further work will be required to develop the evidence base for future policy. Future research may include:

- Assess policy and regulatory instruments to enable, set and implement material consumption targets.
- Addressing how the materials sector interacts with other sectors to understand the extent to which carbon budgets can be shared.
- Determine whether material switching (from hard-to-abate sectors) between product groups provides genuine benefits and an acceleration towards net zero.
- Assess whether regional changes/differences may influence the development of carbon budgets to collectively meet the global targets.
- Analysis and apportionment of the remaining carbon budget for the remaining materials.
- Assess the wider environmental benefits of the proposed material consumption targets.

Appendices

A.1.0 Technical Methodology

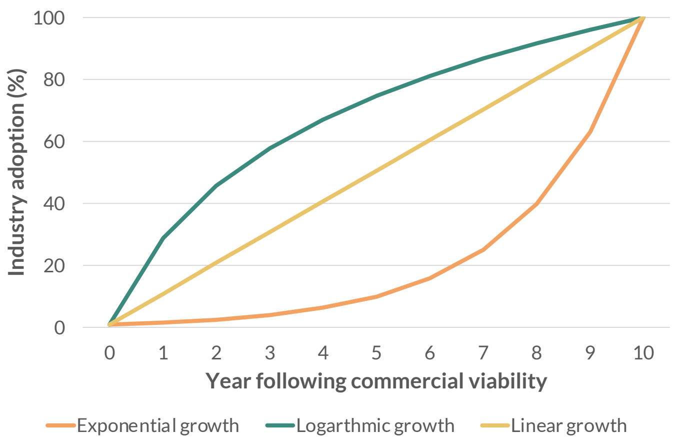
Timing of Interventions

The timing of interventions outlined in the net zero strategies and literature is critical to remaining within the emissions budget. It is anticipated that earlier deployment of breakthrough technologies will raise investment costs and the cost of production in the short term, but the risks of overshoot associated with failing to act are far greater.[27] The timing of interventions has been governed by assessing their technological readiness, and the timelines indicated in the net zero strategies. The total cumulative emissions are sensitive to the timing of implementation and therefore various scenarios have been tested to highlight how critical early actions are in sufficiently reducing annual emissions.

Industry Adoption

In addition to the year of implementation, the model also accounts for the rate at which sectors adopts new technological interventions. The model assumes that only 1% of the industry will adopt a new technology in the year it becomes commercially viable, and that the level of adoption within the industry grows to 100% over the course of 10 years. The total cumulative emissions are sensitive to the growth trajectory associated with the adoption rate. As such, three different trajectories have been explored; exponential growth, linear growth and logarithmic growth. Figure A1.1 demonstrates the different adoption rates over the ten year period dependent on the adoption model chosen.

Figure A.1.1: Industry Adoption of Technology over Time



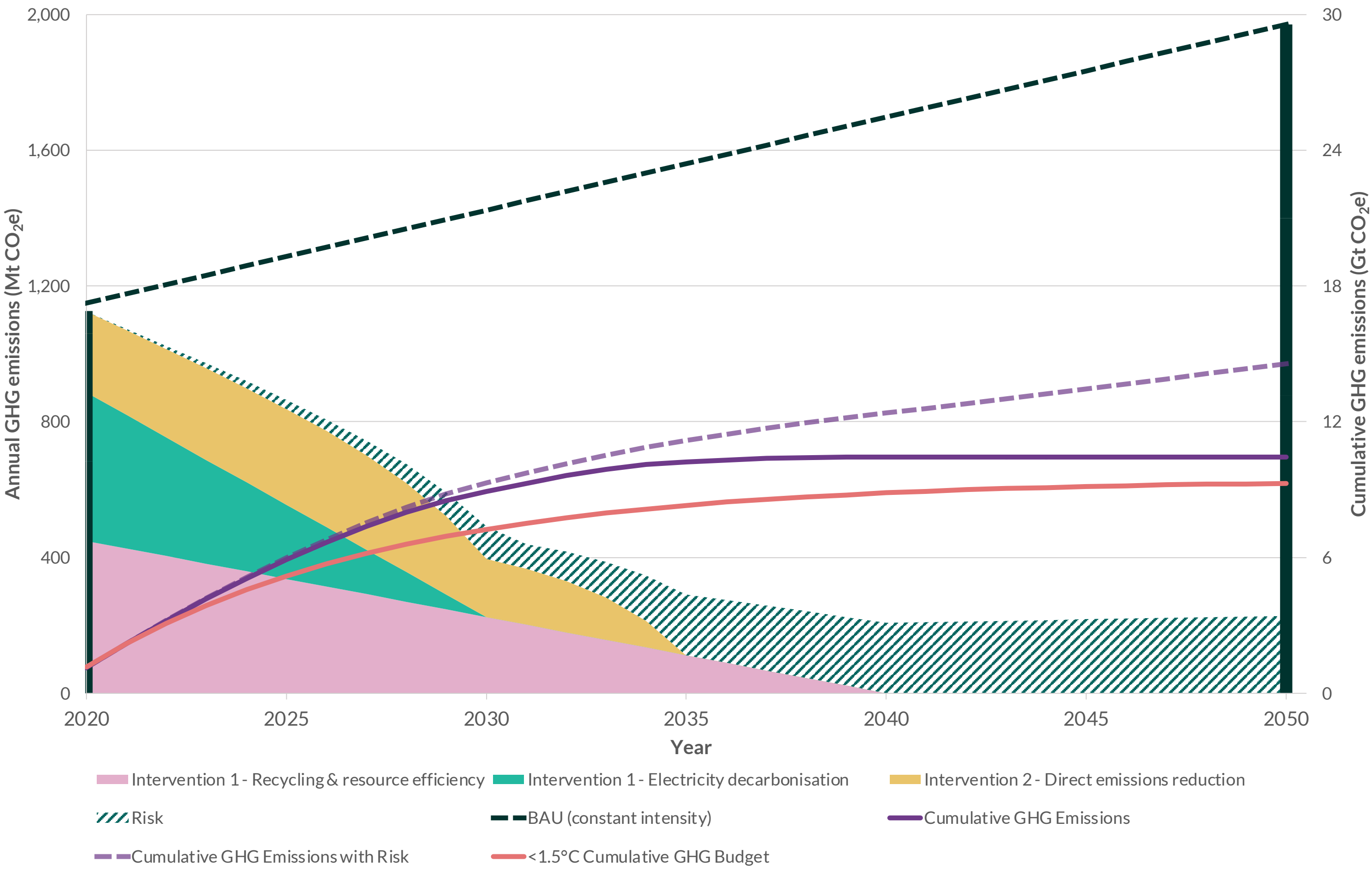
A.2.0 Ambitious Deployment Scenarios

A.2.1 The Aluminium Sector

Table A2.1.1: Year of Technological Implementation in Accelerated Deployment Scenario for the Aluminium sector

Technology		
Electricity decarbonisation	**Initial year of decarbonisation**	**Year of decarbonisation in Scenario**
Electricity decarbonisation	2040	2030
Direct emissions reduction	**Original year of Initial Deployment**	**Year of Initial Deployment in Scenario**
Inert anode technology	2025	2020
Mechanical vapour recompression	2025	2020
CCUS	2030	2025
Green Hydrogen	2040	2025
Recycling and resourceefficiency	**Initial year of decarbonisation**	**Year of decarbonisation in Scenario**
Increasing recycling	2050	2040

Figure A2.1.1: Modelling GHG Emissions for the Aluminium Sector - Ambitious Deployment Scenario

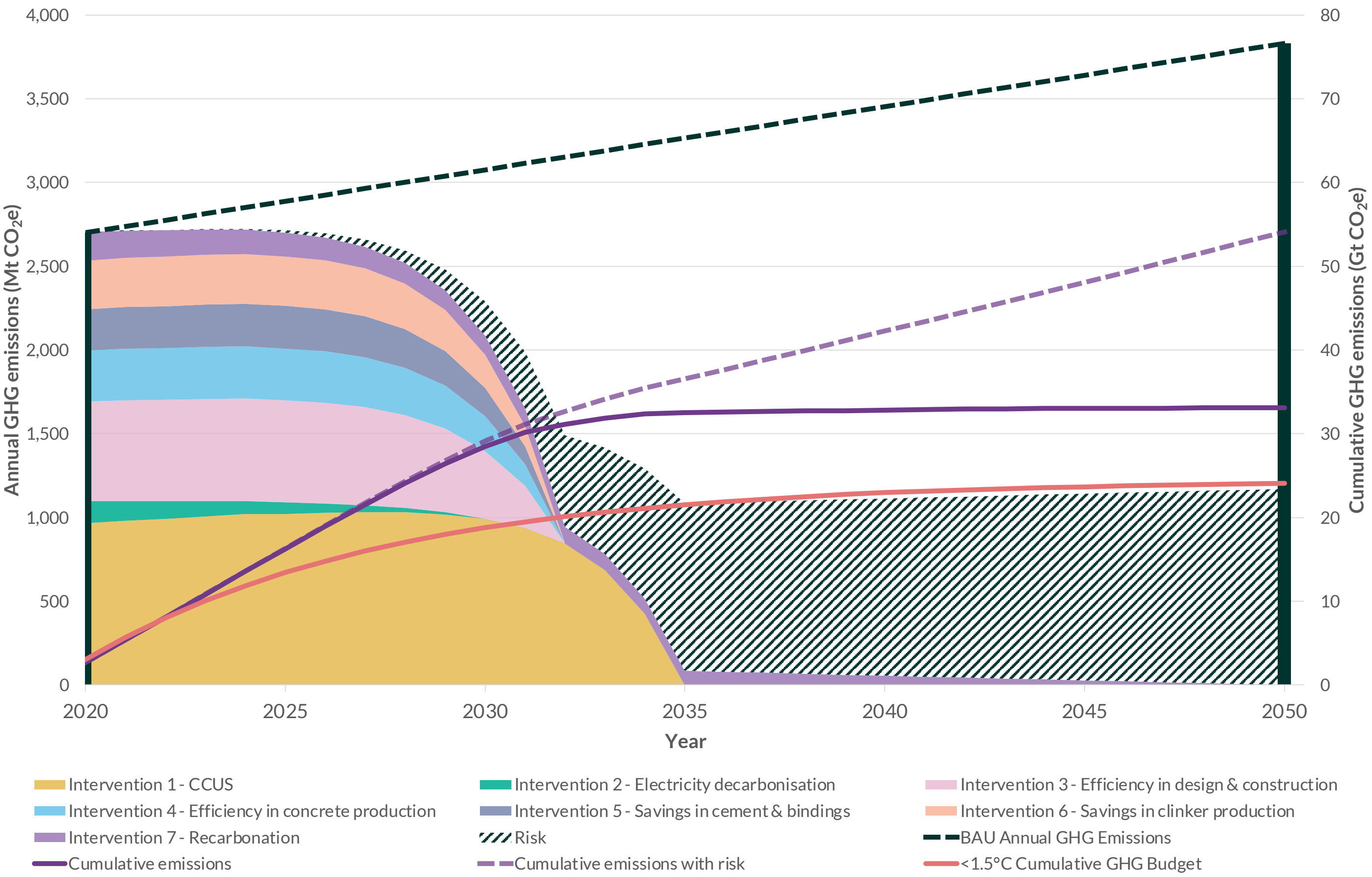


A.2.2 The Cement & Concrete Sector

Table A2.2.1: Year of Technological Implementation in accelerated deployment scenario for the Cement & Concrete sector

Technology	Original year of Initial Deployment	Year of Initial Deployment in Scenario
Technological improvements		
CCUS	2030	2025
Improvements in production efficiency		
Design and construction	2025	2022
Concrete production	2025	2022
Cement and binders	2025	2022
Clicker production	2025	2022

Figure A2.2.1: Modelling GHG Emissions for the Cement & Concrete Sector - Ambitious Deployment Scenario

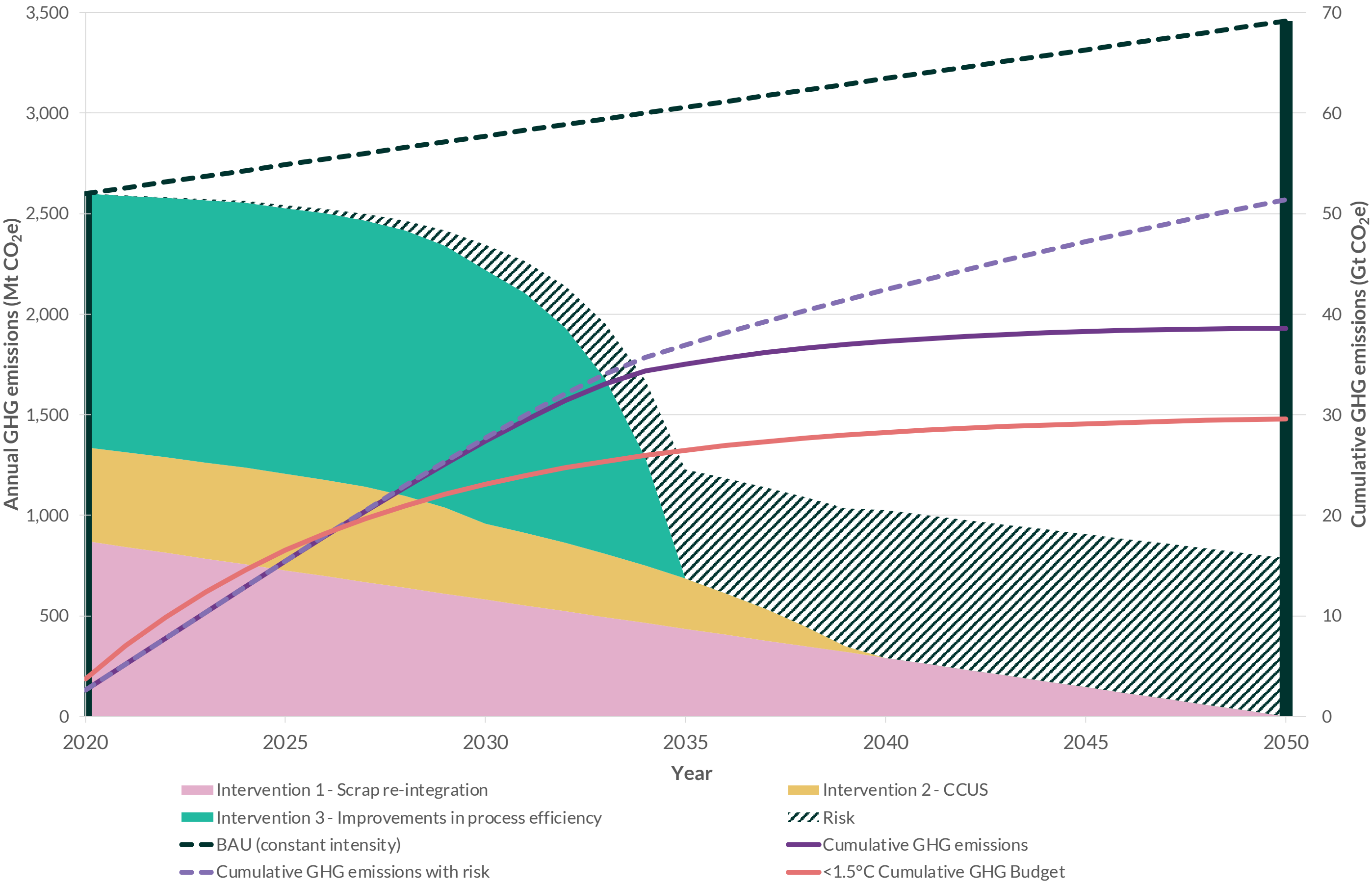


A.2.3 The Iron & Steel Sector

Table A2.3.1: Year of Technological Implementation in accelerated deployment scenario for the Iron & Steel sector

Technology	Original year of Initial Deployment	Year of Initial Deployment in Scenario
Scrap re-circulation	2020	2020
Production efficiency	2030	2025
CCUS	2020	2020

Figure A2.3.1: Modelling GHG Emissions for the Iron & Steel Sector - Ambitious Deployment Scenario

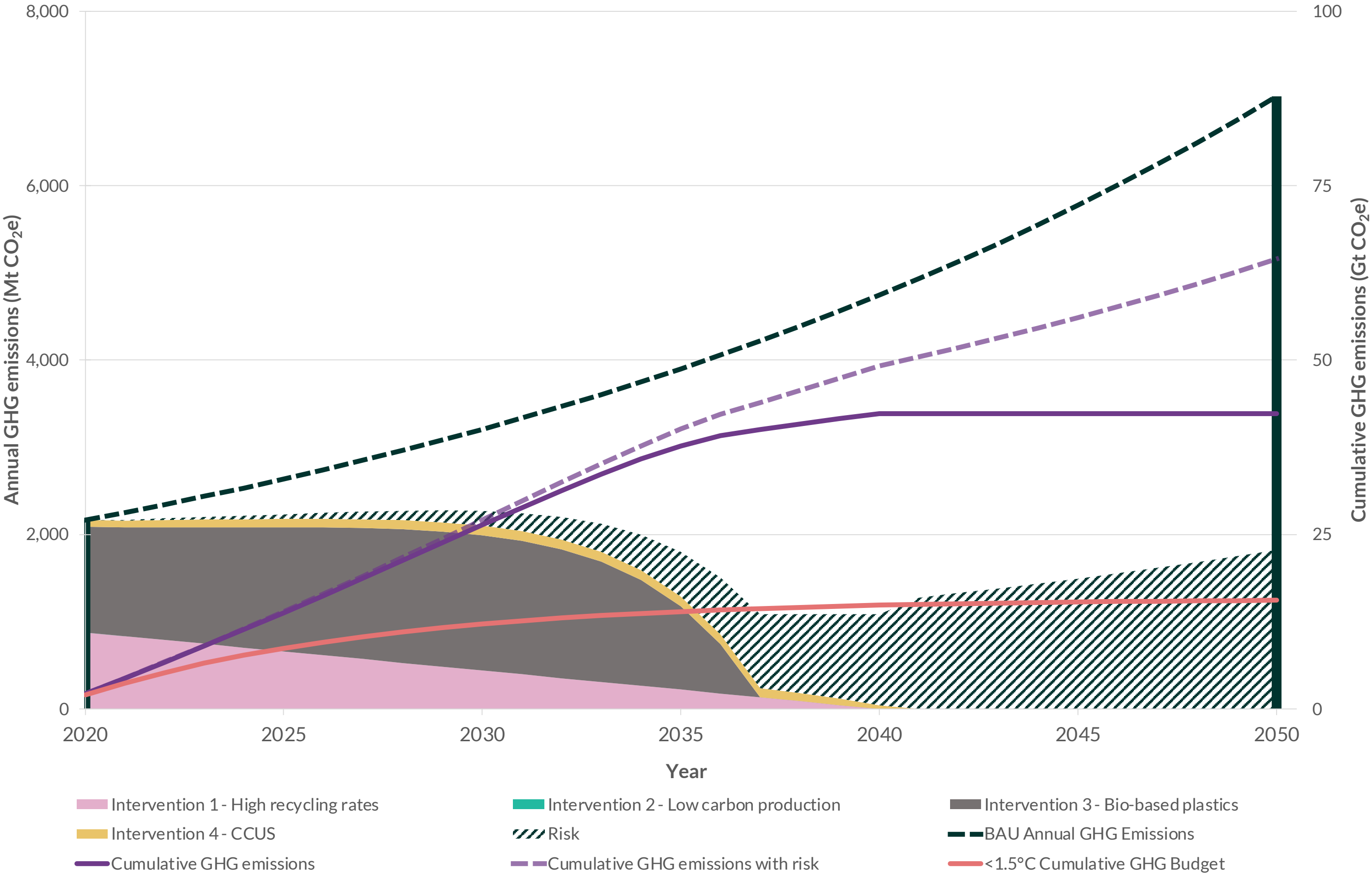


A.2.4 The Plastics Sector

Table A2.4.1: Scenario Risk Factors

Technology	Fossil/Bio-based Mix Scenario	Bio-based Only Scenario
Low carbon production	Medium	-
High recycling rates	Medium	Medium
Bio-based plastics	Low	Medium
CCUS	High	High

Figure A2.4.1: Modelling GHG Emissions for the Plastics Sector - Bio-based Only Scenario



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