Net Zero 2050:

More affordable than ever, if we act now

2022 Climate Scenarios Whitepaper

By Nick Stansbury, Head of Climate Solutions and Justine Schafer, Climate Economist, LGIM Climate Solutions

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Foreword: A shift in focus

Sonja Laud,
Chief Investment Officer

Few issues are as significant to our environment and society, and investment returns, as climate change. The challenge it presents is only becoming more pressing, as the energy transition progresses too slowly – and the geopolitical environment becomes more complex.

At LGIM, we look at the transition through the lens of scenario analysis. This helps us to mitigate the associated risks, and capture the opportunities, on behalf of our clients.

In 2022, we undertook a root-and-branch review of all the assumptions that underpin the scenarios we model, whose main findings we detail in this paper. These scenarios are neither forecasts nor predictions; they are potential pathways we have modeled for the world realizing different climate outcomes.

> The **world**, **policymakers** and **investors** need to **embrace** every legitimate tool in the **decarbonization toolkit**.

Our research suggests the window to achieve a 1.5°C outcome, consistent with 'net zero' emissions by 2050, is closing fast. But it also highlights the surprisingly positive reductions in the cost to achieve such an outcome that we have already seen – and can also expect in the future.

In other words: we are more confident that the world could easily absorb the costs associated with realizing the goals of the Paris climate agreement, while at the same time far less confident that we are on track to do so.

As a result, we conclude that the world, policymakers and investors need to embrace every legitimate tool in the decarbonization toolkit. The pathways that remain to reach net zero by 2050 are those that use every lever.

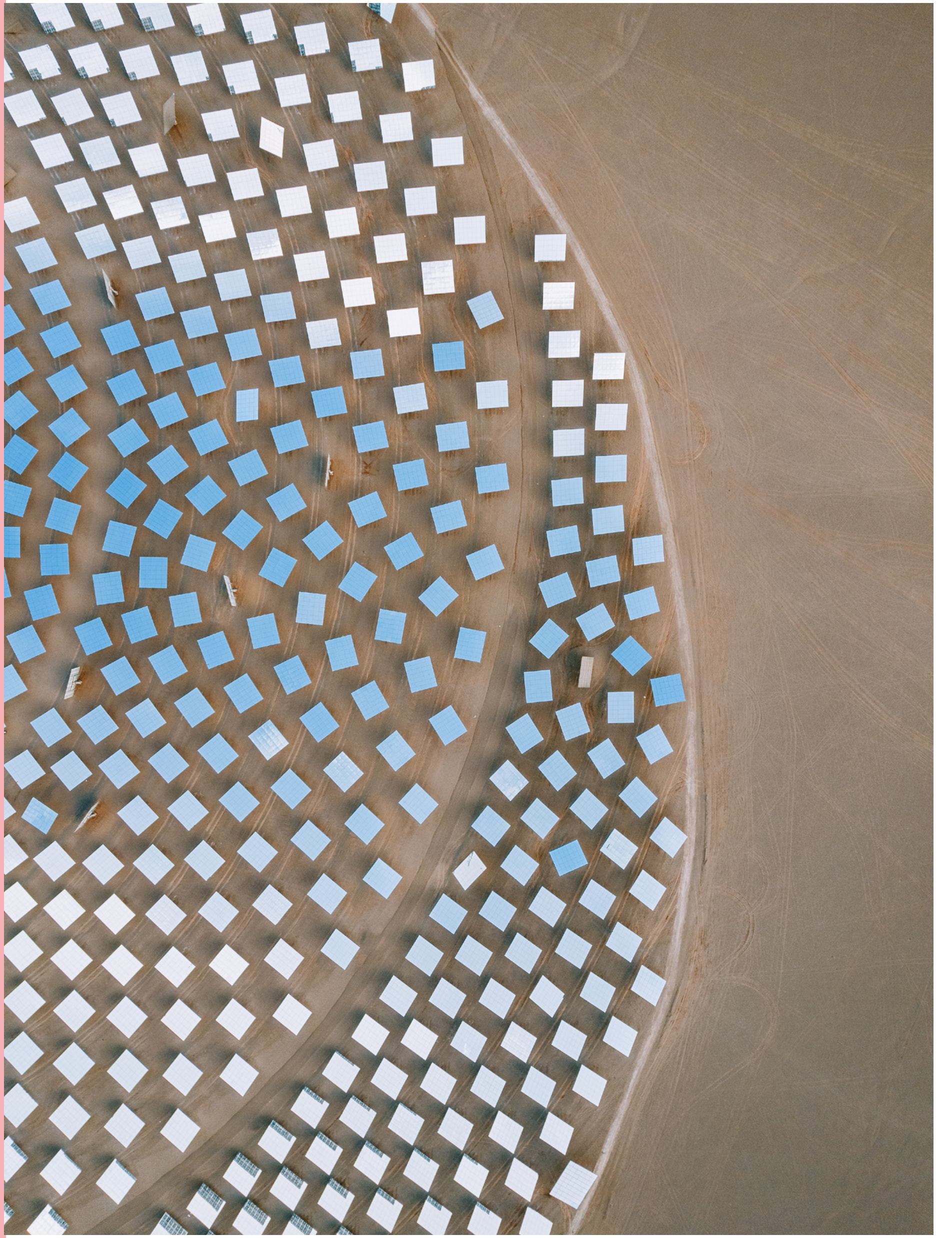
In this context, we remain convinced that engagement with companies critical to the energy transition – with the threat of consequences should they fail to listen – is the best way to deliver the systemic change necessary to meet this challenge. Blanket divestment, in our view, usually means overlooking the problem.

We argue for a shift in focus by investors, to consider how much capital to allocate to those firms that may not yet be fully positioned for a net zero economy, but have the potential to be. These businesses can play a leading role in decoupling economic growth from carbon emissions. We can help them to realize this opportunity.

But we need to be realistic about the road ahead. As time passes, and our worst-case outcomes become more likely, we also think investors need to better prepare for the implications – both in terms of the potential impact on market returns, but also on inflation and volatility.

At LGIM, our purpose is to create a better future through responsible investing. On the generation-defining issue of climate change, we believe this requires the nuanced approach for which we advocate over the coming pages.

This is the only way, in our view, to effect the sustainable, real-world outcomes that we so urgently need.



The importance of scenario planning

The world's energy and land systems underpin every economic activity we engage in, and every aspect of our day-to-day lives. The next quarter century is highly likely to see a dramatic re-engineering of these two interconnected systems. In our view this rebuilding is going to have far-reaching implications for investors, regardless of which climate outcome the world heads towards. It is likely to affect every company and country to whom investors provide their capital.

Understanding these implications is complex. The land and energy systems we depend upon are highly interconnected, and even small changes in one area can have huge knock-on impacts elsewhere. To understand these changes, we make use of 'scenarios' built using energy and land system models to generate internally consistent pathways to different climate outcomes. These scenarios are not intended to be forecasts, but instead represent pathways that are consistent with the assumptions and constraints that those building the scenario believe to be plausible. Scenarios are produced by several different parties: international agencies, oil and gas companies, non-governmental organizations (NGOs) and specialist consultancies. Given the importance of the changes that lie ahead, LGIM has spent many years developing our own scenarios – independently of those produced by third parties – so we can control the data, assumptions and constraints, ourselves.

The assumptions and constraints underpinning our scenarios are not static; they need to be continually updated and improved to reflect the changes that are occurring in the world around us and the dramatic pace of change in technologies and expected costs. In 2022 we undertook a root and branch review of every assumption that underpins our scenarios. This paper outlines the changes we've made, as well as some of the most interesting and relevant potential implications.

The most important word is ‘and’

Historically, in our view, the most overused word used to debate the energy transition has been, ‘not’. We must not depend upon carbon capture and storage. We must not build new nuclear power stations. We must not support the development of blue hydrogen. We must not burn biomass for power. The debate has often been framed in simplistic terms, with one choice set up as mutually exclusive to another. We find this structure increasingly unhelpful. There is, given the dual challenges of complexity and urgency, little room for taking legitimate technology choices or options ‘off the table’. In our view, the modeling is crystal clear: achieving the Paris goals is going to require using virtually every legitimate tool in the energy transition ‘toolkit, together. It is not a question of building renewables or nuclear, but rather deploying capital as fast and effectively as we can into both. We do conclude that certain technology routes may – for cost and efficiency reasons – have a smaller role than some other studies have suggested. For example, we are not as optimistic in many of our scenarios on the adoption of ‘green’ hydrogen as others have been. However, in almost all cases the answer that comes out of our research is ‘and’. We need the whole arsenal. The energy transition is not likely to be a question of investors (or policymakers) excluding one tool to the benefit of others, as has so often been suggested, but will be making the best use of the word, ‘and’.

1.5 degrees – not impossible, but increasingly infeasible

Unfortunately, the window of opportunity to achieve a 1.5°C climate outcome is starting to close at a worrying speed, with 2022 being yet another year of largely inadequate action. After the declines in emissions that occurred during the COVID-19 pandemic (which from peak to trough equaled roughly the same annual rate of change needed globally for the next 30 years to achieve 1.5 degrees), the global economic rebound that followed has led to all those declines being fully unwound, and then some (IEA, 2021). Global emissions are on track to reach all-time highs (IEA, 2022), and we have observed little tangible evidence that this trajectory is likely to change any time soon. Climate science has been clear for some time that the risks as warming increases beyond 1.5°C accelerate dramatically, and the evidence we see today suggests that investors need to start to prepare for these risks to materialize. In our view, the window of opportunity to set the world on a pathway to 1.5°C is closing rapidly, with fewer and fewer plausible routes to achieving it. Something dramatic needs to change: our modeling tells us that a delayed below 2°C scenario is highly economically disruptive and costly – delaying the more ambitious target of 1.5°C is therefore something that the world cannot afford.

...but we believe achieving a Paris-aligned outcome would be cheaper and easier than ever before

Much like other research teams, we have consistently underestimated the pace of cost and efficiency improvements in low carbon energy technologies. In almost every area, our review of the current literature has led us to lower our prior assumptions on costs and, in many cases, increase our assumptions on efficiency. Even though the required pace of decarbonization has increased due to delays to policy action, the reduction in assumed costs more than offsets this. In the scenario pathway we have modeled, transitioning to a below 2°C climate outcome would probably lower global GDP growth rates by a statistically undetectable amount: as little as 1 basis point over the next quarter century. This may sound like a shocking conclusion – transitioning to below 2°C would be so cheap it would not affect long-term economic output to any significant extent – but in our opinion one consistent with other studies.[1]

Costs may not be the most important factor any longer

We are increasingly of the view that the cost of transitioning is no longer an especially relevant factor. A low carbon energy system is now so cheap, that further improvements in costs and efficiencies are no longer likely to have as large an impact on the pace of change as they have had historically.[2] Instead, our modeling suggests that it is the speed at which capital can be deployed into low carbon energy systems that is now the most important driver and most pressing challenge. To follow our Net Zero 1.5°C pathway, we estimate average annual additions to 2050 would have to be 3 times current levels for solar and double current levels for wind. This is far from being just about making capital available - in the context of the wider policy environment, removing bottlenecks like permitting and infrastructure are just as - if not more - important than capital availability to unlock this acceleration.

Science and engineering have already delivered much of the cost reduction that we need.[3] Now, the emphasis is on capital providers, particularly investors and asset owners, to dramatically accelerate the flow of capital into the low carbon energy system of the future. The capital requirements are dramatic – tens of trillions of dollars over the modeling horizon (McKinsey, 2022) – and clean energy investment would need to at least triple in the 2020s for us to be on track for 1.5°C (IEA, 2021).

[1] See, for example (Heal, 2020)
[2] Although we note there are a number of important technology developments that remain either unsolved or substantially too expensive in a number of 'hard to decarbonise' areas, these are the exception rather than the rule
[3] See chapter Cheaper, but no more likely

Land use system must contribute to decarbonization

For the first time in our latest scenarios, we have modeled the required changes to our land system alongside energy.[3] The modeling has confirmed that around 20% of the 'effort' required to achieve the Paris goals needs to come from our land use system – a radical process of changing the way we use our land – to counterbalance the competing demands of biomass, food and afforestation. We have concluded that the implications for land may be some of the most dramatic, and most underappreciated, of all the implications the transition may have.

The economic burden does not fall on the broadest shoulders

One of the most irksome communication challenges climate and transition modelers face is explaining why – in present value terms – the economic costs of climate failure appear so small. In almost all studies, including ours, the costs of failing to achieve the Paris goals appear modest once discounted into present value terms. This does not obviously reconcile with the severity of the physical harms that are likely to manifest over time from climate failure. A large part of this is accounted for by the distortions caused by discounting very large future costs at market discount rates. Even an economic catastrophe 70 or 80 years in the future, if discounted at a sufficiently high discount rate, can appear very modest in present value terms. In this case, discounting is clearly distorting the true severity of the future challenge. Another part can be explained by the high degree of uncertainty, and challenges in effectively modeling, the unprecedented and far-reaching nature of genuine climate breakdown. Very few models claim to be able to accurately capture the economic impact of climate breakdown and the associated human and societal costs.

However, there remains an underdiscussed third component to the problem. In both the case of successful transition, and in the case of climate failure, a vastly disproportionate share of the costs are borne not by the richest countries and people groups, but by the poorest. Put bluntly, the poorest half of the world's population generates only around 10% of global economic output.[5] Therefore, in purely economic terms, catastrophic harm that affects them much more significantly than the richest half results in a disproportionately low direct economic cost – whether certain or uncertain – discounted or undiscounted.

Implications for **land** may be some of the most dramatic, and most **underappreciated**, of all the **implications** the transition may have.

4.We rely on the open-source Model of Agricultural Production and its Impact on the Environment (MAgPIE) for the land use component of the modelling (Dietrich, et al., 2021)
5.LGIM analysis based on (World Bank, 2022)

This challenge also manifests itself just as profoundly when we consider the economic burden of climate success. In a successful, well-ordered transition to the Paris goals, both the aggregate global economic cost and inflationary impact are modest. However, in our modeling the relative impact on GDP and inflation is far greater in the emerging world than it is in the developed, and we expect there will also be a difference in impact within countries. For example, our model shows that the inflationary burden of a low carbon transition in Nigeria is at least four times greater than it is in the UK. This is caused by several underlying factors, including the decarbonization burden increasing with expected economic growth, the mix of goods and services being consumed by country, and the share of food in consumption expenditure (which is higher when disposable income is low).

The unequal nature of this burden is even more pronounced when viewed in its historical context – not only are those most affected by climate failure the poorest globally, but they are also those who have historically consumed a far smaller share of the hypothetical 'per capita' carbon budget – responsible for a minuscule fraction of the current greenhouse gas (GHG) stock in the atmosphere (Ritchie & Roser, 2020).

What are the implications of these 'just transition' considerations for investors? All our modeling (like most other studies) is predicated upon the assumption that the world will pursue the most techno-economically efficient pathway. Yet investors need to recognize the frictional nature of resolving these challenges, with strategies to mitigate the associated risks including engagement and participation in policy development.

Scenario analysis: Many possible climate outcomes

Scenario analysis helps us to understand the strategic implications of possible climate pathways, including the key features of a transition to a net zero economy. We use scenarios to explore the role our organization can play alongside policy and corporate action to mitigate climate risk and support climate opportunity. **Scenarios, whether ours or those from third parties, represent only possible pathways. They are not forecasts or predictions and there is no certainty that any one pathway will be realized. Building our scenarios requires us to make a very large number of assumptions – any of these could prove to be incorrect and this has the potential to materially invalidate all, or key parts, of our scenarios.**

We develop our own bottom-up scenarios of how the world's energy and land systems may evolve to 2050. These scenarios grant us valuable insights into the difficult trade-offs between minimizing short-term climate policy impact and mitigating long-term physical climate change.

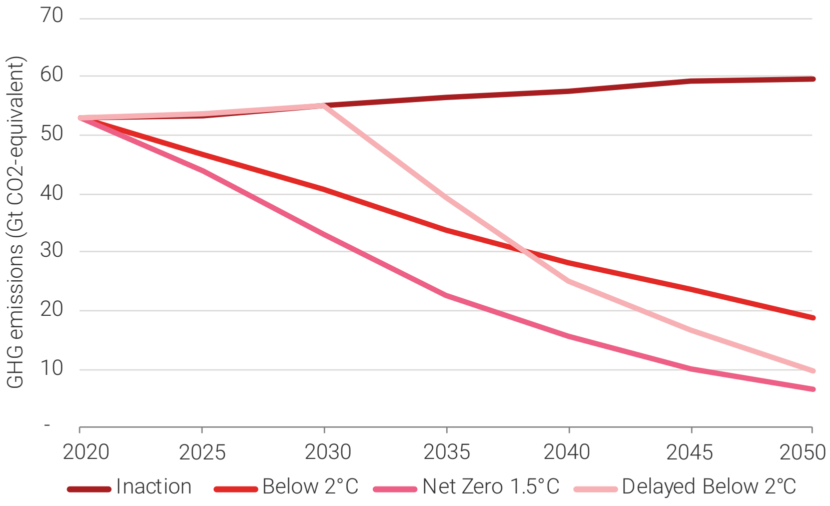
We model four energy pathways:

Scenario	Net Zero 1.5°C	Below 2°C	Delayed Below 2°C	Inaction
Approximate global warming by 2100	1.5°C	<2°C	<2°C	3-4°C
Core narrative	Immediate, highly ambitious action to address climate change leads to a reduction in CO2 emissions to net zero around 2050	Immediate, ambitious policy and investment action to address climate change succeeds in limiting global warming to well below 2°C	Policy and investment action to limit global warming to well below 2°C is delayed to 2030, resulting in much more disruptive change	Global failure to act on climate change means emissions continue to grow at historical rates

GHG emissions in the Inaction scenario continue to grow, ending up around 10% higher than today by 2050, but must gradually fall to around 19Gt and 6Gt in the Below 2°C and Net Zero 1.5°C scenarios respectively. As decarbonization in the Delayed Below 2°C scenario is delayed by 10 years, it must decarbonize faster and further than the Below 2°C scenario, to around 10Gt CO_2e by 2050.

To achieve these emissions reductions, global carbon prices (per tCO_2e) in the Below 2°C and Net Zero 1.5°C would need to reach around \$70 and \$110 by 2030, and \$205 and \$490 by 2050 respectively. Delayed Below 2°C carbon prices do not rise until after 2030 and, as a result, must reach a much higher level by 2050 to achieve the emissions reductions required to stay on track for less than 2°C of warming by 2100. The model sets a carbon price in each period to limit emissions to within the global carbon budget, given the technology options available at that time. This means the carbon price is best thought of as the cost of the last, most expensive tonne of carbon globally abated in each period. There may be many ways in practice that the required price per tonne of GHGs our models imply could be translated into policies – it is not necessarily best implemented through a blanket carbon price. Subsidies for low carbon technologies, sales bans for highly polluting products, cap-and-trade mechanisms: these are just some examples of how carbon pricing could be implemented in practice. Scenarios are a critical input into our LGIM Destination@Risk toolkit, which translates them into company, sector, and portfolio level implications. We use two main metrics to understand asset exposure to climate change: One is climate risk, which describes the potential risk from various climate scenarios to asset valuations. The other is temperature alignment, which assesses the risk our assets pose to achieving various climate outcomes: whether companies are contributing to the changes we need to see according to our scenarios, or whether they are putting them at risk.

Figure 1: Global greenhouse gas emissions (GtCO2e/year)



Source: LGIM Destination@Risk

Global carbon prices (2020 US$/$tCO_2e$)

Scenario	2030	2050
Net Zero 1.5°C	111	491
Below 2°C	71	205
Delayed Below 2°C	0	886

Climate solutions: The most important word is ‘and’

Much of the recent narrative around the energy transition has focused on what technologies we should not rely on, from biomass and hydrogen to carbon capture and storage. While it may be possible to stretch our scenarios to reach 2°C outcomes based on electrification, renewables and batteries alone, we believe this would put unprecedented and infeasible strain on global supply chains, and in fact be less credible than using all available tools at our disposal. It would also not allow us to limit warming to 1.5°C. The world’s scientific authority on climate change, the IPCC, finds that warming is likely to exceed 1.5°C by 2040 at the latest, even along the most ambitious mitigation pathway (IPCC, 2021). This means that virtually all 1.5°C pathways include some amount of temperature overshoot and rely critically on carbon removal measures to reduce temperatures to within the limit later in the century.

Our decarbonisation scenarios envision an energy system that, by 2050, relies on a primary energy mix dominated by renewables, biomass and nuclear, but with a continued, if greatly reduced, role for natural gas and oil. It utilises hydrogen as a novel energy carrier in hard-to-decarbonise segments of the economy, in combination with carbon capture and storage technology. Afforestation and avoided deforestation provide crucial negative emissions to the decarbonisation effort. Pricing non-CO_2 GHGs incentivises emissions abatement in agriculture, for example, through changes to animal feed or investment in animal waste management facilities.

Our case studies further highlight the ‘and’ not ‘or’ principle across three dimensions:

Power generation: solar, wind and nuclear

Renewables and nuclear energy are often pitted against each other when it comes to decarbonization efforts. While we recognize that social acceptance of nuclear energy varies across the globe, there are regions where nuclear represents a well-established, comparatively cheap, and crucially, zero carbon route of generating baseload electricity alongside hydro, storage and some remaining natural gas

Hydrogen: green and blue

'Green’ hydrogen from biomass gasification or electrolysis powered by renewable electricity is often emphasised as the only environmentally viable option for hydrogen production. Yet we believe that ‘blue’ hydrogen, produced using natural gas with carbon capture and storage (CCS), has a role to play, particularly in regions where natural gas is cheap and abundant, like the Middle East

Carbon sequestration: CCS and afforestation

Natural sequestration is sometimes compared unfavourably to technical sequestration using CCS. We find that both are important in our decarbonization scenarios. CCS is a crucial technology in hard-to-abate sectors in industry and can be used to decarbonize the production of baseload power generation and hydrogen from natural gas. It is also, in our view, critical if the energy system is to produce negative emissions, by combining CCS with bioenergy production or using Direct Air Capture. At the same time, afforestation is likely to be invaluable in removing carbon from the atmosphere and can have co-benefits such as maintaining biodiversity. Our modelling indicates that both methods of carbon sequestration will be needed to balance out emissions from hard-to-abate sectors which need to continue to rely on fuels other than electricity

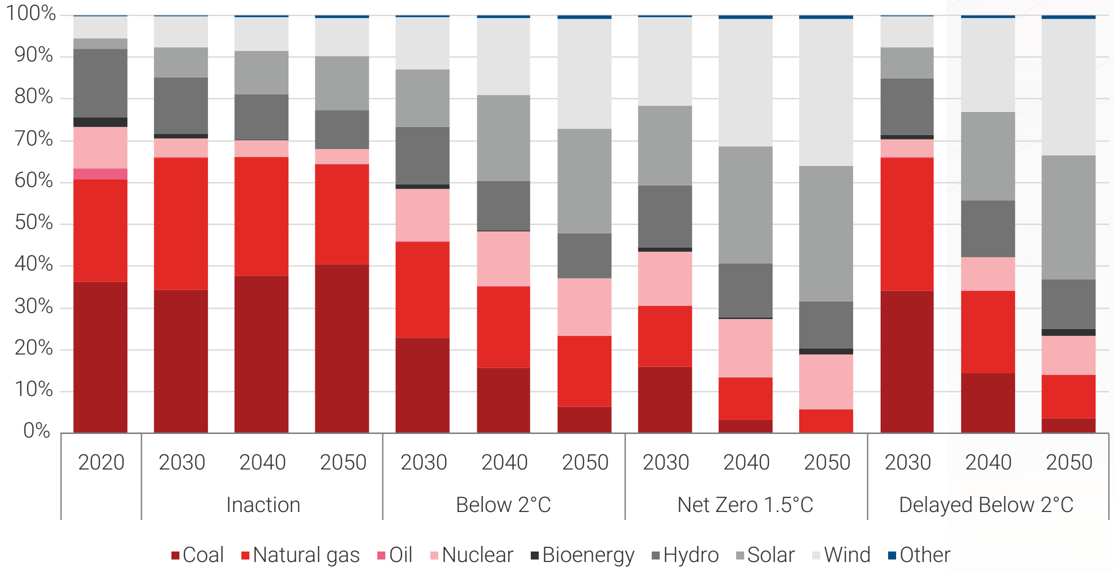
Of course, not all technologies are viable everywhere. Nuclear power generation is politically sensitive and high cost in Europe and North America but represents a practical option for zero carbon baseload generation in Asia. Cost and availability of different energy sources varies by region, changing the economics of what is feasible to deploy at scale. A global optimization model such as ours can take these affinities and constraints into account and find the least-cost path to limiting emissions within a carbon budget. To allow the world to transition cost effectively, we must be aware of the strengths and limitations of technologies, including whether they may find applications in some regions rather than others, utilizing economies’ natural advantages and existing infrastructure where possible.

We have conducted extensive benchmarking of our scenarios against external scenario-modeling efforts including those released by the Central Banks and Supervisors Network for Greening the Financial System (NGFS) and the International Energy Agency (IEA). We find that while different models may have different emphases, the key underpinnings of their transition scenarios are the same. Well-established and novel technologies work in tandem to deliver fundamental change to the production and use of energy in the global economy. For most variables, our scenarios are well within the range of scenarios, including solar and wind generation and carbon capture and storage. However, we diverge slightly on a few key points, including fossil fuel demand persisting for longer, having a deliberately more disruptive Delayed (Below 2°C) pathway and higher projections for hydrogen demand.

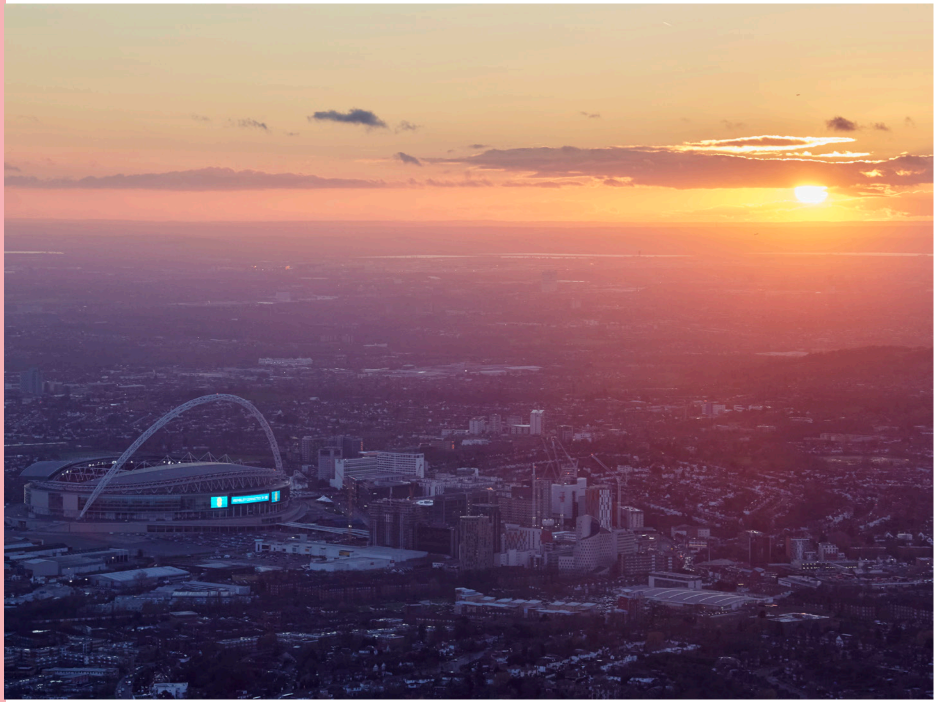
Case study: Power generation

Electrification of end use sectors relies critically on a decarbonized power grid to underpin emissions reductions – making the power generation sector one of the most critical early levers for decarbonization. By 2050, around 40% of final energy consumption comes from electricity in our decarbonization scenarios, with global capacity in the Net Zero 1.5°C scenario nearly doubling by 2030 and quadrupling by 2050 compared with today.

Figure 2: Share of global power generation by asset type



Source: LGIM Destination@Risk



It is **imperative** to a well-below 2°C future that **no new coal generation be built**, starting immediately.

Decarbonising global power generation must begin with a move away from coal-fired generation. It is imperative to a well-below 2°C future that no new coal generation be built, starting immediately. Coal-fired power is phased out entirely in our Net Zero 1.5°C scenario by 2030 in developed markets, and around a decade later everywhere else.[6] This means that many facilities, especially in emerging markets, would need to close before the end of their economic life, after an average 25 rather than 40 years. In our Below 2°C and Delayed Below 2°C scenarios, the pace is somewhat reduced, with some coal remaining in the system by 2050. While global coal capacity increases by more than 20% on today's levels in the Inaction scenario, most of this growth occurs after 2030 in emerging markets. The Delayed scenario hence has only a little more coal capacity by 2030 than the Below 2°C scenario, yet it must phase it out slightly faster to achieve the required emissions reductions.

Alongside the phase out of coal, both solar and wind capacity need to be built at unprecedented speed and expand into developing regions with very little deployment to date. By 2050, solar and wind account for 50-70% of global power generation in our decarbonization scenarios. Global solar and wind additions were 133GW and 93GW in 2021, respectively (IRENA, 2022). To follow our Net Zero 1.5°C pathway, average annual additions would have to be 3 times current levels for solar and double current levels for wind. Much of this would be driven by developing regions with abundant solar resource and historically little deployment, particularly countries in Asia Pacific, the Middle East, Africa, Central and South America. Altogether, these regions' (excluding China) share of solar capacity grows from 14% today to 44% by 2050.

6. Whilst our scenarios are not an input into our public commitments on coal (LGIM's Policy on coal 2022), in our view the modelled pathway is consistent with our targeted phaseout schedules in that policy

While solar and wind capacity growth greatly reduce the carbon footprint of global power generation, they will increase its land footprint – although we believe this issue is often overstated. Solar and wind generation require at least 10 times as much land per unit of power produced as coal or gas generation, including land disturbed in the production and transportation of fossil fuels (Gross, 2020). In addition, while traditional fossil fuel power generation tends to be located near sources of demand, solar and wind will need to be built where resource availability is best, increasing transmission infrastructure requirements. Wind siting is especially challenging given the sensitivity of output to a) location – doubling incoming wind velocity increases potential output by eight times; and b) size – doubling blade length from 50 to 100 metres increases potential output by four times (Thunder Said Energy, 2021). Offshore wind vastly reduces land use. The total land requirement from solar and onshore wind capacity in our Net Zero 1.5°C scenario would grow from 27 million hectares (mHa) in 2020 to around 140 million hectares by 2030 and around 400 million hectares by 2050 – that's nearly 12 times the land area of Germany, or 3% of global land area.[7]

However, most of the land can be utilized for other purposes, such as agriculture. Almost 90% of the land requirement is for onshore wind, of which only approximately 1% or less would be occupied by roads, turbine foundations and other equipment. The remainder would be available for other activities such as farming and ranching (U.S. Department of Energy, 2015). When accounting for this, the land use requirement for all solar and wind capacity in our Net Zero 1.5°C scenario by 2050 comes down to only 50 mHa, or 1.4 Germanys. Accordingly, recent research has highlighted solar power generation, alongside nuclear and direct air capture, as one of the most land-efficient abatement options available (in tonnes of CO_2 abated per acre per year) (Thunder Said Energy, 2020).

An electricity grid that relies mostly on solar and wind will still need to meet demand when the sun does not shine, or the wind does not blow. The model underlying our scenarios ensures the system can meet 'peak' demand – such as a particularly hot day in summer where many buildings simultaneously use air conditioning units (the peak demand pattern varies by region). To ensure that demand can be met in these conditions:

- Nuclear, hydro and gas with CCS provide reliable baseload generation. These three sources make up 30% of global power generation in 2050 in our Net Zero 1.5°C scenario. By 2050, gas is the only remaining fossil fuel in power generation in our Net Zero 1.5°C scenario, yet some coal remains in the system in our Below 2°C scenarios

- Battery storage provides flexibility. Around 3,700GW of grid-scale storage capacity is in use by 2050, as well as around 800GW of off-grid storage capacity in our Net Zero 1.5°C scenario. Deploying this many batteries in the power sector while simultaneously transitioning the transport sector to battery electric vehicles means our scenarios depend critically on major scaling-up of the supply of minerals such as copper, lithium, nickel, and manganese

> An **electricity grid** that relies mostly on solar and wind will still **need to meet demand** when the sun does not shine, or the wind does not blow.

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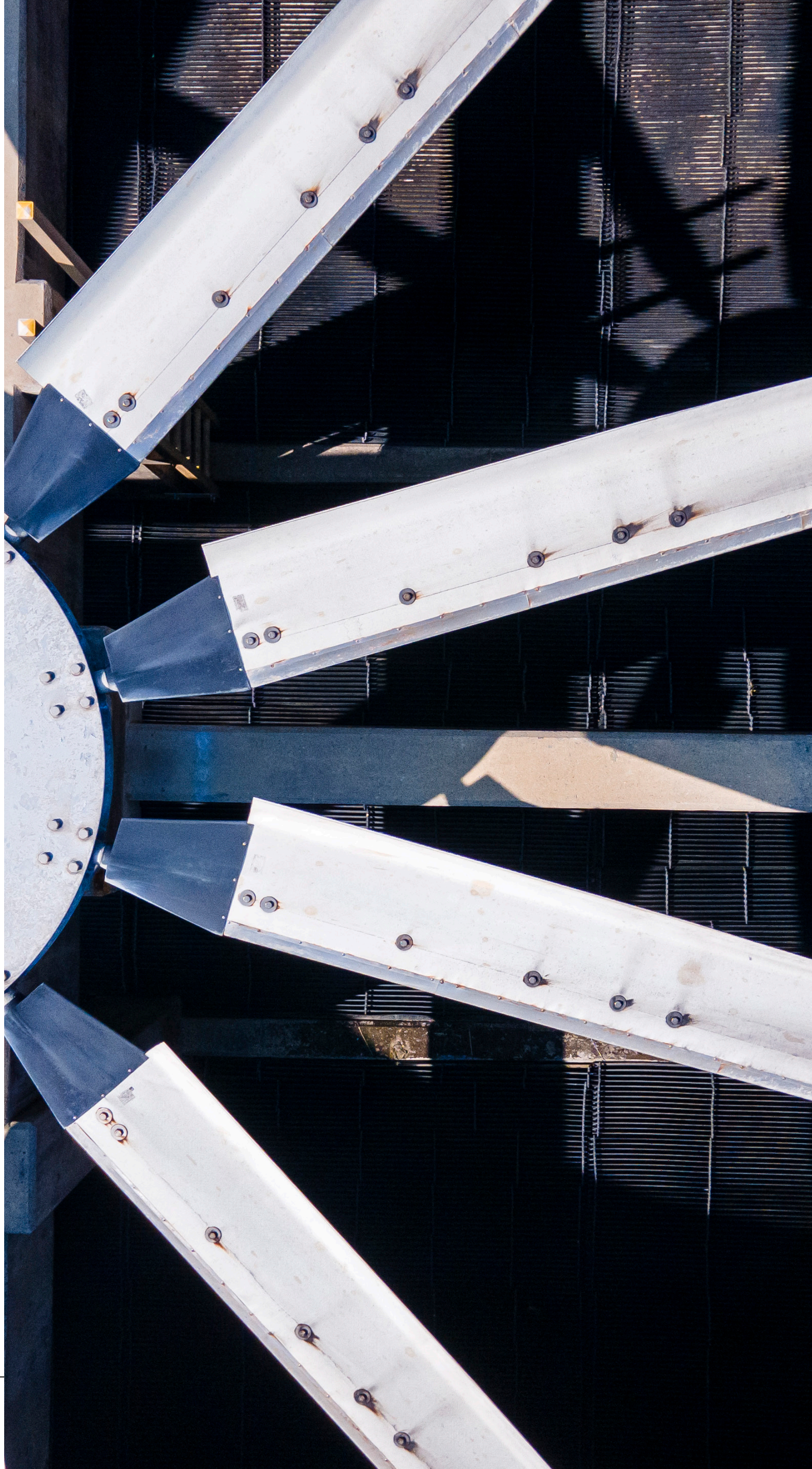
[7] Assuming 100 acres per MW for onshore wind and 8 acres per MW solar

Nuclear capacity[8] would have to grow from around 400GW today to nearly 600GW by 2030 and 1,000GW by 2050 in our Net Zero 1.5°C scenario. Similarly, our Below 2°C scenario sees nuclear capacity grow to around 450GW in 2030 and 850GW in 2050. Much of this growth is driven by China, where nearly one fifth of power generation by 2050 comes from nuclear. That's a third of global nuclear power generation by 2050, compared to China's share of around 15% today (Ritchie, Roser, & Rosado, Energy, 2022). However, other developing regions such as Central and South America, the Middle East, India, and other Asia Pacific also all contribute to the growth in global nuclear capacity in our scenarios.

We do not believe that growth in nuclear capacity is likely in the UK, the USA and Europe unless there is a significant shift in policy environment. While new plants may be built to replace the ageing existing fleet, as is the plan in the UK, net growth in capacity seems highly unlikely. As a result, we have restricted growth in nuclear capacity in our Below 2°C and Inaction scenarios in these regions to allow no net new capacity.[9] In Europe, the UK, and North America, our Inaction scenario instead sees a steady decline in nuclear capacity to 2030 as aged plants are retired and no replacements are built. This means the Delayed scenario begins from a much lower starting point on global nuclear capacity in 2030 than the immediate action scenarios – about half of today's capacity. Even at an accelerated deployment speed, it cannot catch up to the nuclear capacity established in our immediate action scenarios by 2050. The exception to the stringent constraints on nuclear deployment in these regions is our 1.5°C scenario, which relies critically on a paradigm shift in climate policy, including on nuclear as a source of relatively cheap, zero-carbon baseload electricity. There is significant policy uncertainty around the future of nuclear power which could affect this materially.



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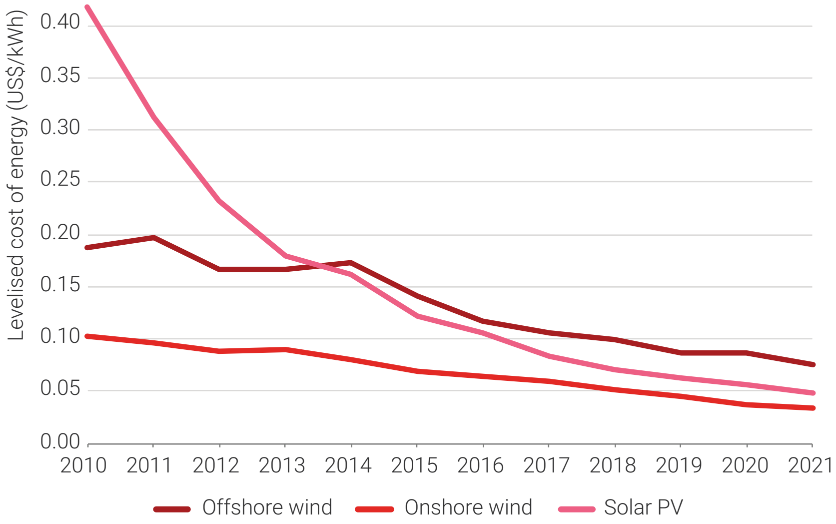
[8] We recognise that nuclear power remains a controversial technology. In some scenarios produced by 3rd parties nuclear power has a smaller role than in our scenarios. Our scenarios are not forecasts and without the policy support envisaged nuclear power could play a smaller role than in our scenarios.

[9] We have not imposed similar constraints on nuclear growth in Japan given recent policy shifts but note that should there be renewed political opposition to nuclear in the country, this assumption may be invalidated

Realising the Paris goals: Cheaper, but no more likely

Costs of key decarbonization technologies such as renewables and electric vehicles have seen significant decline over the last decade. As shown in the chart right, between 2010 and 2021, the levelized cost of electricity (LCOE) of newly commissioned solar PV projects (utility-scale) fell by 88%, by 68% for onshore wind and 60% for offshore wind. Utility-scale solar PV and hydropower were 11% cheaper in terms of global average weighted LCOE, and onshore wind was 39% cheaper, relative to the cheapest new fossil fuel capacity option in 2021 (IRENA, 2022). Over the same period of 2010-21, average battery prices in the electric vehicle industry fell from over $1,000/kWh in 2010 to less than $150/kWh in 2021 (McKerracher, 2022). Both renewables and electric vehicles are critical technologies to the energy transition as they are among the cheapest decarbonization options at our disposal.

Figure 3: Levelized cost of energy



Source: (IRENA, 2022)

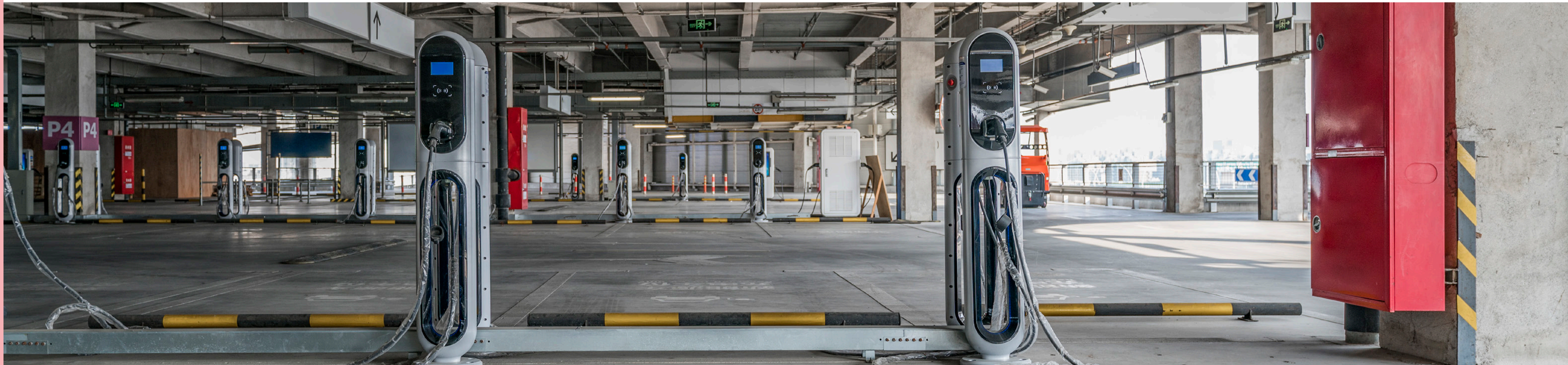
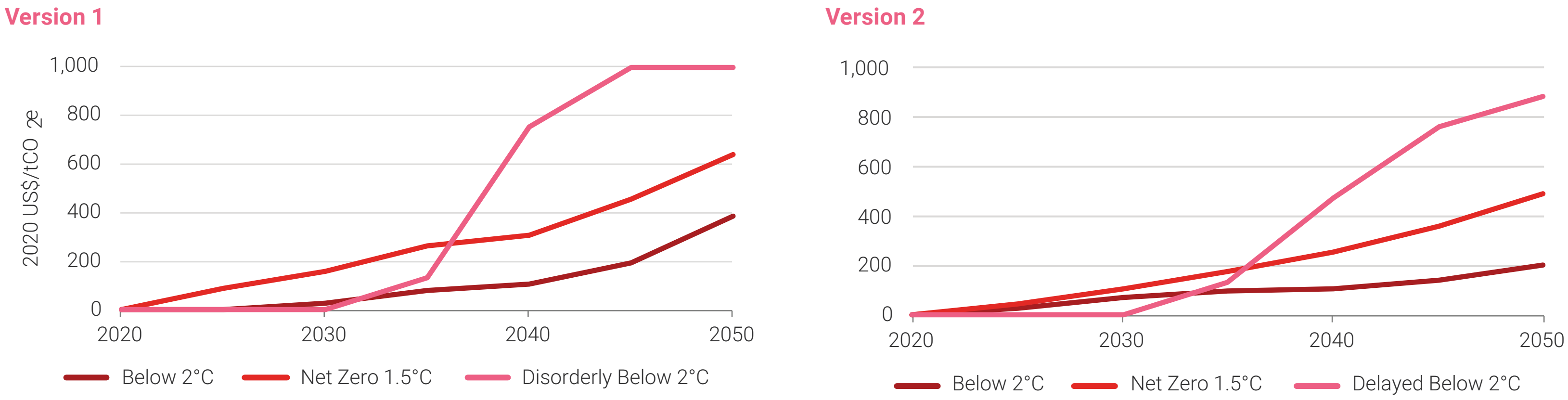


Figure 4: Carbon prices in our previous scenarios (version 1, left) versus this release (version 2, right)



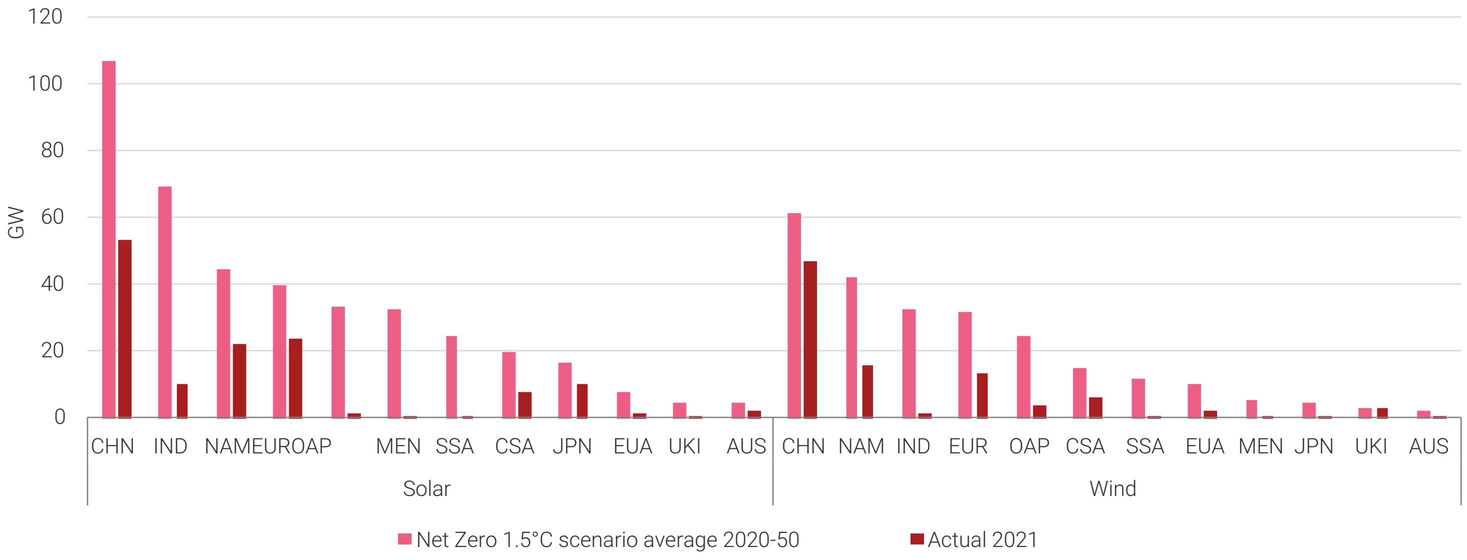
Source: LGIM Destination@Risk

This has led to our scenarios becoming cheaper across the board, with Paris-compliant warming outcomes now cheaper than we have ever seen them – but not necessarily more likely. Compared with last year, 2050 carbon prices have fallen from \$1,000-900/tCO$_2$ in the Delayed, from \$600-500/tCO$_2$ in the Net Zero 1.5°C, and from \$400-200/tCO$_2$ in the Below 2°C scenario. Risk to GDP and inflation have also come down, although they are still significant in the Net Zero and Delayed scenarios. Our Below 2°C scenario continues to pose very little risk to GDP or inflation on a global level: by 2050, cumulative impact from transition and physical risk on global GDP would amount to around 3% – that's a loss of around one basis point per year. However, the same is not true for our other scenarios: although costs have come down for both the Delayed and the Net Zero scenarios, there are reasons to remain cautious on their likelihood and cost.

For one, deployment of renewables has not accelerated sufficiently to put us on track for 1.5°C. Global solar and wind additions were 133GW and 93GW in 2021, respectively (IRENA, 2022). To follow our Net Zero 1.5°C pathway, average annual additions to 2050 would have to be 3 times current levels for solar and double current levels for wind. Much of the renewable capacity added in our 1.5°C scenario is built in regions with near zero deployment today, such as Asia Pacific (excl. China and India), the Middle East and Africa. Around 20% of the global population live in countries with excellent solar PV conditions, primarily in the Middle East and Africa (ESMAP, 2020). Yet this potential is not currently being harvested to provide clean energy. Even China, the country with the highest solar capacity additions in 2021, is only around halfway to what would be required annually to 2050 to put us on course for 1.5°C.

To follow our **Net Zero** 1.5°C pathway, average annual additions to **2050** would have to be **3 times** current levels for **solar** and double current levels for **wind**.

Figure 5: Net annual capacity additions of solar and wind, modelled versus actual



Source: LGIM Destination@Risk, 2021 actuals based on (IRENA, 2022)

In addition, emissions have kept rising despite, at the time of writing, only around nine years of current emissions remaining before the carbon budget for 1.5°C is exhausted (Usher & Matthews, 2021). Our model operates in five-year time steps, so the next model point we have is for 2025. Now in 2023, halfway there, it is starting to look less and less likely that a reduction in annual emissions from around 55 $GtCO_2e$ in 2020 to less than 45 $GtCO_2e$ in 2025 can be achieved. Instead, 2022 is likely to be the highest annual level of GHG emissions ever recorded, at around 58 $GtCO_2e$ (Kharas, Fengler, Sheoraj, Vashold, & Yankow, 2022). So, while costs of the 1.5°C scenario have fallen in this analysis, as of the start of 2023 this is contingent on emissions being cut by 4 $GtCO_2e$ every year for the next three years. For context, the largest absolute decline in emissions (observed during the COVID-19 pandemic) was 2 $GtCO_2e$ in 2020 (IEA, 2021).

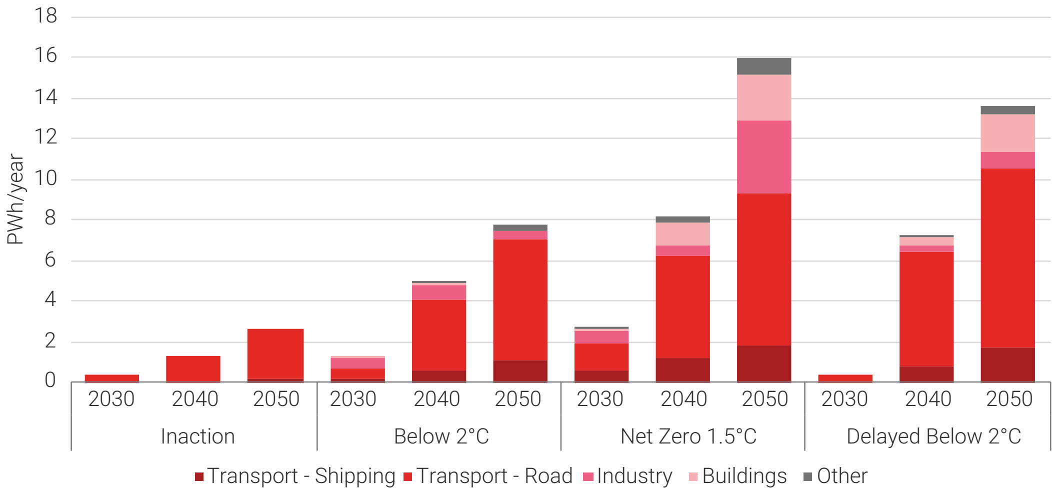
Of course, many technologies remain where cost is still very much a barrier to deployment, particularly in the absence of carbon pricing, including carbon capture and storage solutions. It is these technologies, often associated with the hardest-to-abate sectors such as cement and shipping, that drive up the cost of the 1.5°C and the Delayed scenarios.

Case study: Hydrogen

Demand

The largest new source of demand for hydrogen[10] in our scenarios is the transportation sector. Neither the road freight nor goods shipping segments are candidates for widespread direct electrification: required batteries would be very heavy and large, reducing valuable cargo space, limiting distances travelled, and increasing costs considerably.

Figure 6: Novel sources of hydrogen demand by scenario



Source: LGIM Destination@Risk

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[10] We focus here on new sources of hydrogen demand, rather than existing hydrogen demand and supply (around 75Mt H2 in 2021 (IRENA, 2022).

Ammonia, which is produced from hydrogen, grows to around two fifths of marine fuel consumption by 2050 in the Net Zero 1.5°C scenario. It wins out against hydrogen as a fuel because its higher density reduces onboard storage requirements, allowing more room for cargo. Ammonia can be used through a fuel cell, which increases fuel efficiency, or in internal combustion engines. We have found that the additional capital cost of fuel cells compared to internal combustion engines outweighs the efficiency improvement, meaning that internal combustion engines dominate the transition to ammonia.[11]

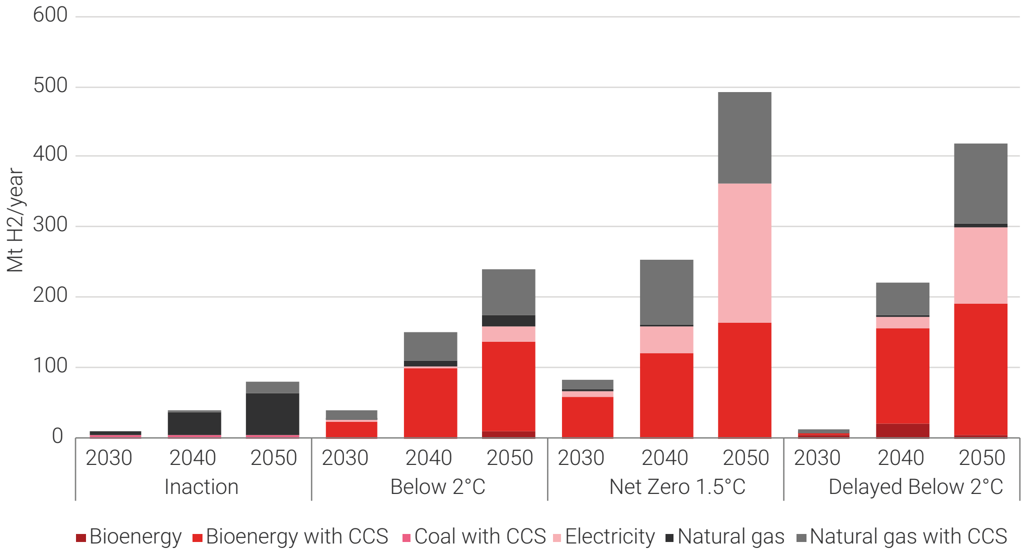
By comparison, the road freight sector transforms further and faster, with hydrogen accounting for around 60% of total fuel consumption by 2050 in the Net Zero 1.5°C scenario – here, in fuel cells – primarily driven by medium and heavy goods vehicles. In the van segment, where vehicles are smaller and lighter, battery electric vehicles dominate, resulting in electricity accounting for around 10% of road freight fuel use by 2050. Diesel still contributes around 30% of fuel consumption by 2050.

Hydrogen is also used as an alternative fuel to natural gas in industry, particularly in iron and steel. Hydrogen-fueled direct reduction of iron is considered one of the most promising decarbonization options in the sector and sees considerable uptake in our Net Zero 1.5°C scenario, alongside a continued move to secondary steelmaking in electric arc furnaces.

Supply

There are three hydrogen production routes we focus on in our scenarios: electrolysis, reformation, and gasification. Electrolysis uses electricity to convert water to hydrogen and, when relying on 100% renewable energy, is zero-carbon. Hydrogen can also be produced in reformers, which use a gas source to generate heat for a reforming reaction that produces hydrogen and CO_2. Gasification transforms a solid fuel, in this case biomass, into syngas, which can be separated into purified CO_2 and hydrogen streams. Both reformation and gasification produce CO_2 regardless of gas source or feedstock and hence are core candidates for carbon capture and storage technology.

Figure 7: Production of novel hydrogen supply by asset type



Source: LGIM Destination@Risk

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[11] This conclusion is subject to some technical uncertainties.

The cost of electrolysis is highly dependent on the cost of input electricity. When continuously taken from the grid, which balances supply and demand using costly baseload generation, electricity tends to be relatively expensive compared to natural gas or biomass. However, electrolyzer flexibility in ramp-up compared to the other two hydrogen production routes would allow the use of electricity at times of the day when it is cheapest. This is particularly relevant in regions where solar power is cheap and abundant, such as China, India, other Asia Pacific countries and Central and South America. This is where we see most electrolyzer capacity built in our decarbonization scenarios.

We find that biomass gasification with CCS is initially a high-cost option, but quickly becomes economic as rising carbon prices highly reward negative emissions.[12] The deployment of this technology is relatively scenario-agnostic across our decarbonization pathways, with around 150-200Mt H2 produced via this process across the three scenarios by 2050. It is highest in regions with cheaper biomass resource available, such as Central and South America. Similarly, hydrogen capacity from natural gas with CCS is deployed where natural gas is cheapest compared to biomass and electricity, most prominently in the Middle East and North Africa region.

We find that **biomass gasification** with CCS is initially a high-cost option, but quickly **becomes economic** as rising carbon prices highly reward **negative emissions**.

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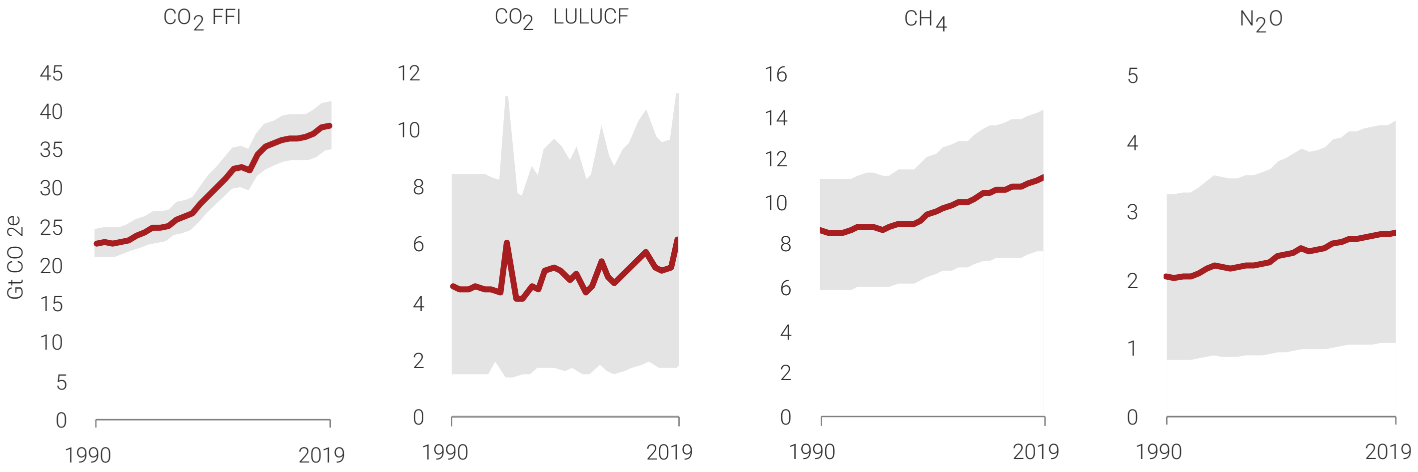
[12] This conclusion is contingent upon our modelling on biomass availability, and would be subject to revision if these assumptions prove incorrect

Simultaneous transitions: Land and energy

Despite representing a large share of global GHG emissions, land emissions, particularly CO_2 emissions from deforestation, are much more uncertain than fossil fuel driven emissions. Agriculture, forestry and land use (AFOLU) contributed around 22% of anthropogenic GHG emissions in 2019, with as much as half of these CO_2 emissions predominantly from deforestation (IPCC, 2022). The range of uncertainty around these emissions is considerable: For the contribution of CO_2 from land use, land use change and forestry (LULUCF) in 2019, estimates range from 2-10GtCO$_2$ in 2019. By contrast, estimates of the CO_2 emissions from fossil fuels and industry (FFI) range from 35-41GtCO$_2$, a much smaller uncertainty range. For methane (CH_4) and nitrous oxide (N2O), which are predominantly caused by agricultural activities such as fertilizer application and enteric fermentation of ruminants, emission ranges are also wide at 3-5GtCO$_2$e and 1-3GtCO$_2$e in 2019, respectively. This uncertainty arises from the variety of methodological approaches and assumptions in use, with the main conceptual difference between global models arising around the boundary of 'human-induced' emissions.

Figure 8: Historical GHG emissions



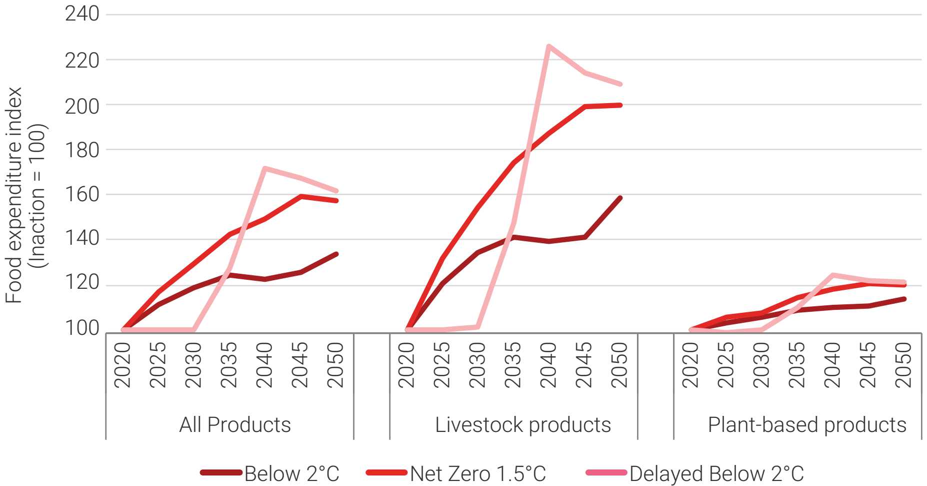
Source: (IPCC, 2022)

Nevertheless, the land sector is crucial to decarbonization: It accounts for around 20% of total GHG emissions reductions by 2050 in our decarbonization scenarios, while also providing the biomass required for bioenergy-related emissions reductions in the energy sector. Land emissions are directly targeted by our carbon pricing mechanism, which extends beyond CO_2 to CH_4 and N_2O.

The most important decarbonization lever for land use emissions is forestry, followed by agricultural practices. We delve deeper into the subject of CO_2 emissions mitigation through afforestation and avoided deforestation in our carbon sequestration case study. Examples of mitigation options in agriculture include feed supplements, improving animal waste management practices and optimizing fertilizer use. In general, methane and nitrous oxide emissions are less simple to abate than carbon dioxide, with estimated 2100 abatement potentials of 60% and 40%, respectively (Lucas, van Vuuren, Olivier, & den Elzen, 2007). Investment in yield increasing technologies results in higher agricultural productivity in our decarbonization scenarios, compared to the Inaction scenario.

While not accounted for as land use sector mitigation, biomass used for bioenergy in the energy system is provided by the land system. Bioenergy is the most land-intensive energy option and hence provision of biomass must be carefully constrained so as not to exert undue pressure on other parts of the land system, such as food production and biodiversity (IPCC, 2022). We have considerably revised the biomass constraints we set the energy model due to insights gained from land use modeling, particularly when it comes to the Delayed scenario. This scenario previously relied heavily on bioenergy with carbon capture and storage (BECCS) technology, particularly in the power sector. Our new Delayed scenario shows that with less biomass available, most of it is used to produce biofuels and hydrogen instead.

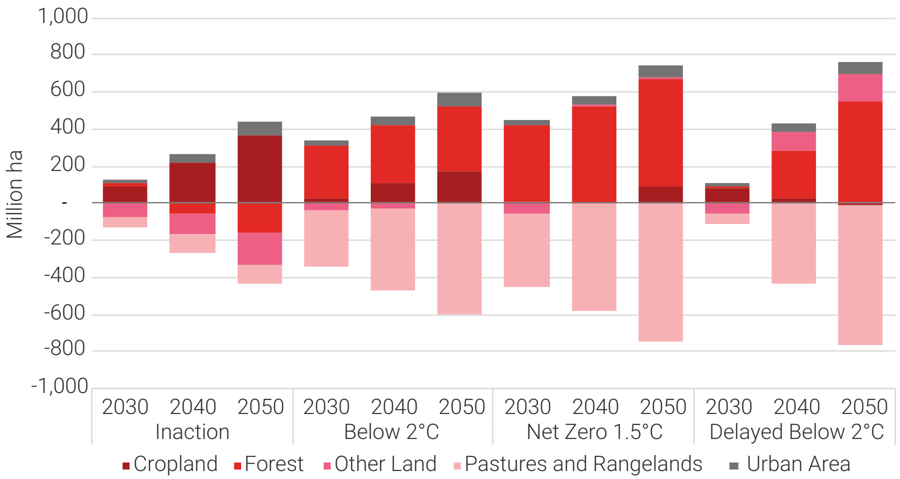
Figure 9: Global food expenditure index relative to Inaction scenario



Source: (IPCC, 2022)

The most **important decarbonization** lever for land use emissions is **forestry**, followed by agricultural **practices**.

Figure 10: Land cover change relative to 2020



Source: LGIM Destination@Risk

A low carbon transition, by pricing land emissions and increasing competition over limited land resource, could increase food prices considerably. Beef is the most emissions-intensive food product per kg. when compared to other types of meat and crops, almost three times the next most emissions-intensive meat (lamb and mutton) (Ritchie, 2020). Livestock meat products experience significant increases in price due to carbon pricing and land competition, around 2.3% real inflation per year to 2050 in the Net Zero 1.5°C compared to the Inaction scenario, or a cumulative doubling over the period. Overall food price pressure is more moderate, due to lower increases in the prices of plant-based food product prices: cumulative increases of around 60% by 2050, or 1.5% per year in the 1.5°C scenario. In all product groups, price pressure in the Below 2°C is about half that of the 1.5°C, and the Delayed, while reaching around the same cumulative level of inflation by 2050 as the 1.5°C, does so in less time, meaning that annual price pressure after 2030 is much higher, and with more volatility.

These impacts on food prices are not a foregone conclusion, but rather a product of our assumption that dietary composition does not change across pathways. We currently assume the same amount of beef consumption in our Net Zero 1.5°C scenario as in our Inaction scenario, as we were interested in the impact of this on prices. However, this assumes that there is no response among consumers as prices for some food products rise more than others. Even holding the share of meat consumption constant and increasing the share of pig and poultry meat could significantly reduce emissions as these animals do not produce methane. Additionally, reducing the amount of waste in the food system – around 17% of total food produced globally today (UN) – could lower demand for agricultural production and similarly reduce food price pressure.

To summarize the impacts of our scenarios on the land system, it is worth examining changes in land cover to 2050. Net forest cover grows in all decarbonization scenarios by 2040, compared to continued reduction in global forest cover in the Inaction scenario. Much of the net forest growth takes place on pasture and rangelands, incentivized by carbon pricing. At the same time, food and biomass demand growth result in some cropland area expansion in all scenarios over the period to 2050. Despite the reallocation of land to forests across our decarbonization pathways, the amount and composition of food production remains the same as in the Inaction scenario. Carbon pricing incentivizes investments in yield increasing technologies, resulting in higher agricultural productivity in decarbonization scenarios relative to the Inaction scenario.

The overall reduction in land use and land use change CO_2 emissions from the Inaction scenario to the Net Zero 1.5C scenario in 2050 is around 3Gt CO_2. This includes an additional 1Gt CO_2 of carbon sequestration from regrowth by 2050, as well as mitigation of 2Gt CO_2 per year in gross land use change emissions.[13]

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[13] We note that there are potentially serious issues to consider around water scarcity, some, not all of which are captured in the land use modelling

Case study: Carbon sequestration

Nearly all modeled pathways to Paris-compliant outcomes involve some form of carbon sequestration. Carbon sequestration describes the process of capturing carbon dioxide and transporting it into long-term storage in oceans, soils, plants (particularly forests) and geological formations.

There are two major categories of carbon sequestration relevant to the energy transition:

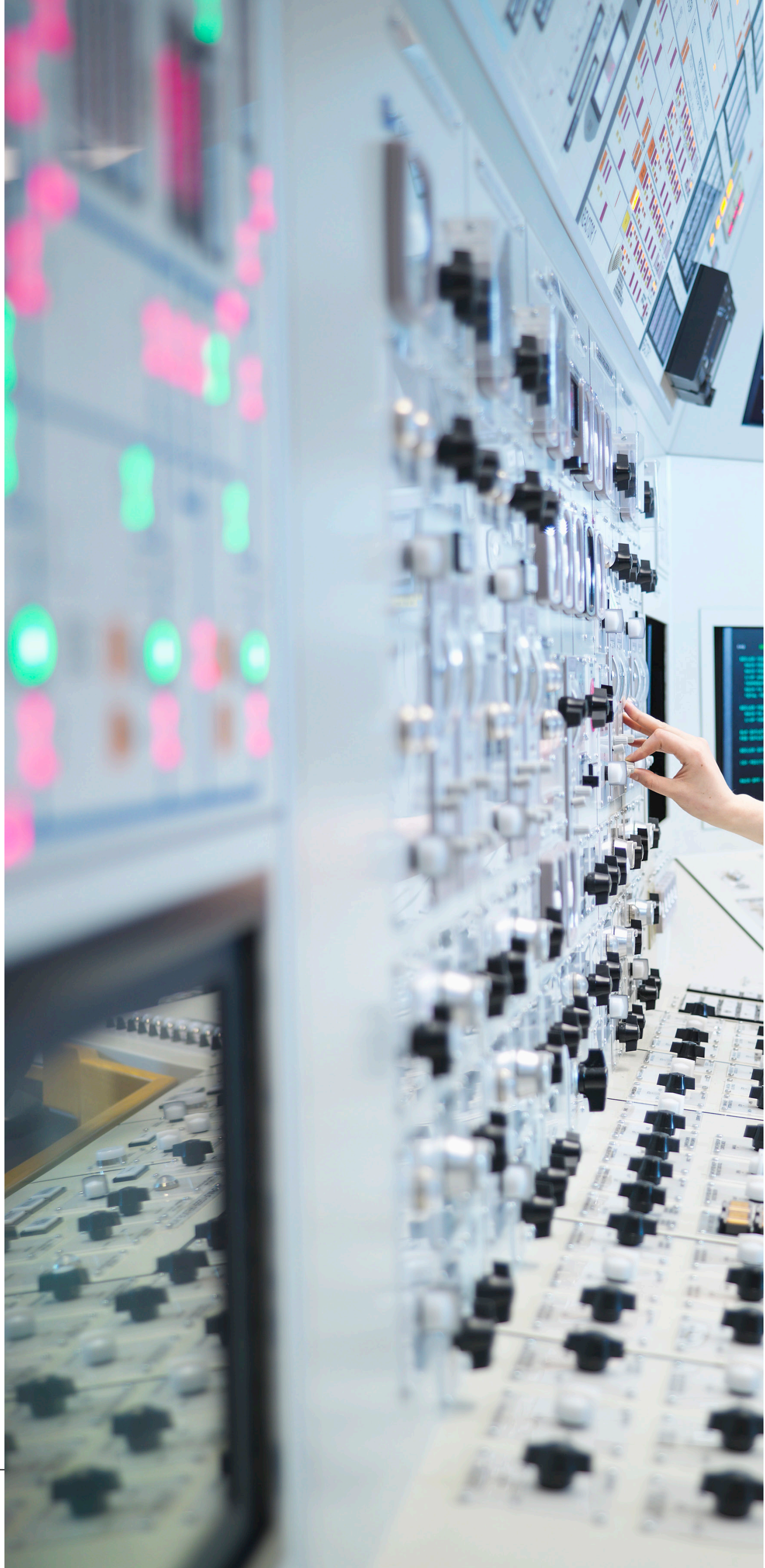
Technological

This includes use of carbon capture and storage (CCS) technology on industrial and power plants, as well as direct air capture (DAC), which filters carbon directly out of the atmosphere and stores it permanently, usually in geological formations

Natural

Natural vegetation captures and stores carbon dioxide as it grows and releases it when cleared or burnt. In our view, the largest opportunities for utilizing natural carbon sequestration as part of the energy transition are through bioenergy, afforestation, and reforestation

To stabilize temperatures at any level, carbon dioxide emissions must eventually reach net zero. Every tonne of CO_2 emitted into the atmosphere contributes to further increase in temperature. Many climate scenarios with ambitious temperature targets initially overshoot the warming target, and then rely on net negative emissions to bring temperatures back down. However, not all carbon sequestration results in a net removal of carbon dioxide from the atmosphere. Carbon capture and storage added onto a power plant running on natural gas, for example, may capture a large proportion of the carbon dioxide that would otherwise be emitted into the atmosphere at the source, but does not reduce the existing CO_2 concentration in the atmosphere. It is therefore important to distinguish between carbon sequestration and carbon removal.

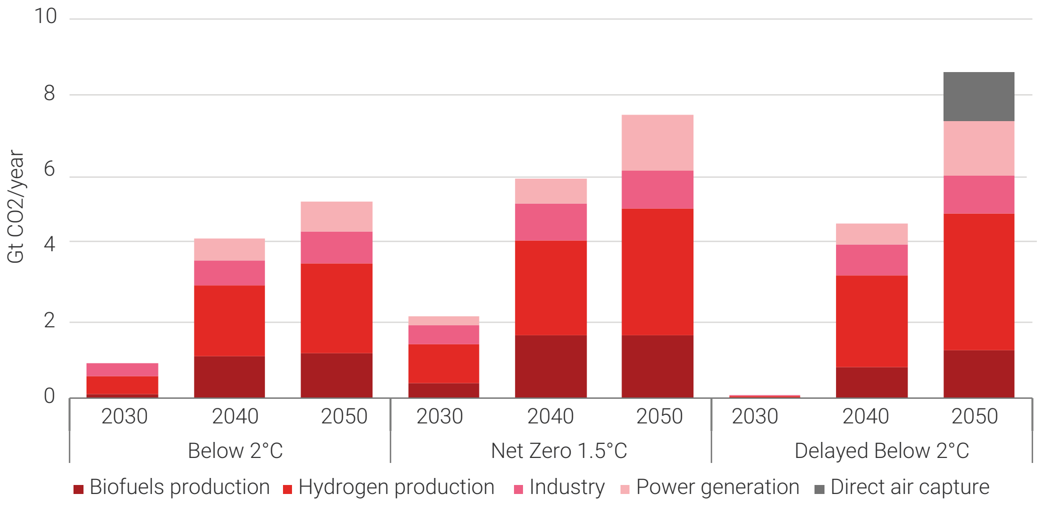


Technological sequestration

CCS is deployed in our immediate action scenarios starting in 2030, growing by 2050 to 5Gt CO_2 captured and stored per year in the Below 2°C scenario; around 8Gt CO_2 in the Net Zero 1.5°C scenario and nearly 9Gt CO_2 in the Delayed Below 2°C scenario – that's equivalent to all global emissions from the transport sector today (Ritchie & Roser, 2020). We do not think that carbon capture and storage technologies are likely to be deployed at scale prior to 2030, as many are still in the small-scale industrial pilot stage today. Around half of the carbon captured and stored in our decarbonization scenarios is from the production of hydrogen with bioenergy or natural gas, explored further in the hydrogen deep-dive.

In the industry sector, CCS is a critical decarbonization lever for cement and steel, which have limited abatement options available. Production of cement is the third-largest contributor to anthropogenic emissions source of carbon dioxide after fossil fuels and land use change (Andrew, 1928-2018, 2019). Total cement emissions, including fossil fuel use and process emissions from clinker production, were 2.7Gt CO_2 in 2021, or 7% of total global energy-related CO_2 emissions (Andrew, 2022). The iron and steel industry similarly contributed another 7% (EIA, 2022). While there is some way both industries can go by means of energy efficiency, fuel switching and alternative production routes, CCS is a key enabling technology for deep decarbonization.

Figure 11: Technical carbon sequestration by application



Source: LGIM Destination@Risk

CCS also has a role to play in power generation, primarily in combination with natural gas, which serves as a source of baseload generation in a highly renewable grid. We do not see power from bioenergy with CCS for power generation being a major lever in our scenarios, as the bioenergy is instead used to produce biofuels and hydrogen with CCS.

Our **estimate** of **CO_2** stored between 2030 and 2050 in the Net Zero **1.5°C** scenario is just above **100 Gt CO_2**

DAC is too expensive to be economic in our immediate transition scenarios but could play an important role should the transition be delayed. While capital and operating costs may be as low as \$450/tCO_2, energy costs could add more than \$250/tCO_2 to this cost, raising the overall cost to above \$700/tCO_2. At this price, we do not see DAC as a credible option in our immediate transition scenarios, but we do see it play a significant role in our Delayed Below 2°C scenario. Costs are likely to be highly regionally variable, as they will depend critically on the costs of input energy. We find that uptake of the technology is concentrated in the middle east, where natural gas is a cheap and abundant heat source for the process. The further climate action is delayed, the more relevant this technology is likely to become, as delay inevitably depletes the carbon budget more quickly, and requires substantial carbon removal to bring cumulative emissions back down.

While there is vast global capacity for storing CO_2, there are practical constraints on deployment of storage facilities. Estimates from high-level geological analysis indicate a potential of anywhere between 8,000 to 55,000 Gt CO_2 global storage capacity (IEA, 2021). Our estimate of CO_2 stored between 2030 and 2050 in the Net Zero 1.5°C scenario is just above 100 Gt CO_2 – seemingly inconsequential in this context. Even if the annual storage amount remained constant from 2050 to 2100, we would only get to just under 500 Gt CO_2 stored this century in our most stringent scenario.

Yet technical, financial and institutional barriers to CO_2 storage are likely to be pervasive, limiting the actual usable capacity this century. In practice, sustainable injection rates for the site will need to be determined with sufficient confidence and will have to match source capture rates over long periods. In countries with limited oil and gas industry experience, detailed geological information has not previously been collected, presenting a barrier to effective site assessment and permitting. In our scenarios, we have set constraints on the amount of carbon that can be safely captured to 2050 by drawing parallels to historical oil and gas production growth. This limits deployment in countries less likely to have detailed geological information available.

Natural sequestration

Deforestation is a core issue to address as part of a Paris-compliant climate transition. Land is both a source and sink of carbon dioxide, as natural vegetation and soil store carbon but release it into the atmosphere when cleared or burnt. Deforestation in particular releases large amounts of CO_2 every year, partially offset by re/afforestation. Recent estimates indicate a global mitigation potential from halting deforestation of 3.6 (+/-2) Gt CO_2 per year to 2050 (FAO, 2022). In our immediate action scenarios, we assume countries honor the commitments made in nationally determined contributions (NDCs) to the Paris Agreement when it comes to avoided deforestation, other land conversion and re/afforestation. In the Inaction and Delayed scenarios, countries only honor the national policies that have already been implemented on these issues.

In addition to national commitments on forestry, carbon pricing creates incentives for afforestation and agricultural intensification. While in the Inaction scenario, global forest cover continues to decrease in favour of cropland and pasture, we observe net forest cover growth in all decarbonization pathways by 2040. Much of this growth takes place on pasture and rangelands, as regrowth of natural vegetation. Cropland growth is also reduced compared to the Inaction scenario, with higher investments in yield increasing technologies resulting in higher agricultural productivity in our decarbonization scenarios.

Total afforested area grows by 200mHa in the Below 2°C scenario and around 300mHa in the Delayed Below 2°C and Net Zero 1.5°C scenarios over the period from 2020 to 2050.[14] This implies an area nine times the size of Germany to be covered in forest over the period to 2050 in the Net Zero and Delayed scenarios, or around 2% of global land area. For context, forests currently cover 31% of global land area (FAO, 2022). Much of this forest growth takes place early in the period, with 160mHa and 230mHa already afforested by 2030 in the Below 2°C and Net Zero 1.5°C scenarios, respectively. The Delayed lags as policy only starts after 2030 but catches up quickly and reaches a similar area afforested as the Net Zero 1.5°C scenario by 2050.

Forest growth due to climate policy is concentrated in a handful of regions: China, India, Latin America, and the US. In our immediate action scenarios, the implementation of China's NDCs result in nearly 100mHa of afforestation in China by 2030. Similarly, in India, 30mHa afforestation is implemented in line with NDCs by 2030. By contrast, in the Delayed Below 2°C scenario, where afforestation is only incentivized by carbon pricing and NDCs are not implemented, we observe afforestation of up to 150mHa and 50mHa by 2050 in Latin America and the USA respectively. That's compared to 120mHa and 30mHa by 2050 in the Net Zero 1.5°C scenario in the two regions. In other words, where afforestation takes place highly depends on countries' national agendas as well as the global policy environment. National forest policy could be driven by many considerations other than maximizing global production of forest carbon credits, such as biodiversity, natural heritage and timber production.

Bioenergy used in BECCS applications adds further competition for limited land resource. Most of the new bioenergy supply our scenarios rely on is comprised of purpose-grown, second-generation bioenergy crops such as poplar and eucalyptus, rather than the food crops (such as sugar, starch and oilseeds) that make up first generation biomass. There is also a limited supply of ligno-cellulosic residues available from agriculture and forestry that contributes to fulfilling biomass demand. Compared to our previous scenarios, this iteration has much more limited access to combined biomass resource.

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14. Given the level of spatial aggregation of the land use model used, it is not possible to distinguish between afforestation and reforestation effectively

A 'just' transition?

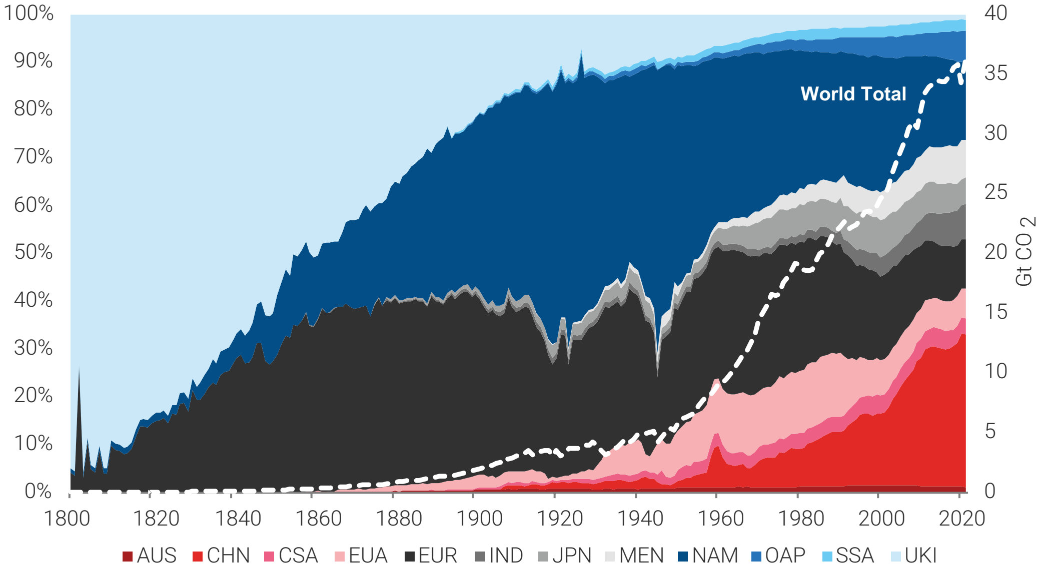
What if the world's poorest are left behind?

Many of today's most populous regions have contributed little to cumulative anthropogenic emissions. More than 15% of the current global population resides in India, but the country has contributed less than 5% to cumulative CO_2 emissions since 1800. On the opposite end of the spectrum, the US has contributed around a quarter of cumulative CO_2 emissions since 1800, but today accounts for less than 5% of the world's population (Ritchie & Roser, 2020). Globally, the 10% of households with the highest emissions per capita contribute up to 45% of global consumption-based GHG emissions from households. Per capita net anthropogenic GHG emissions range from 2.6-19 tCO_2e across regions, with a global average of 7.8 tCO_2e. More than two-fifths of the global population lives in countries with emissions of less than 3 tCO_2e per capita, and a substantial share of these lack access to modern energy services (IPCC, 2022).

More than **15%** of the current global **population** resides in India, but the country has **contributed less than 5%** to cumulative CO_2 emissions **since 1800**.

Yet across all our scenarios these countries are hardest hit by macroeconomic climate risks. As the chart below shows, the Middle East, India, Africa and other Asia Pacific regions are among the worst-affected regions in terms of GDP risk in both our 1.5°C and Inaction scenarios. By contrast, the UK, Europe, Japan, and North America are much less affected in both scenarios, with impacts below the world average. Generally, transition risks hit these regions harder because even though they have fewer emissions per capita, they are expected to grow significantly in terms of both economic output and population over the coming three decades. Their baseline emissions growth is hence much higher – and hence costly to abate – than developed countries with moderate growth trajectories.

Figure 12: Share of annual CO_2 emissions by region, 1800-2020 (left); Total world emissions (right)



Source: (Ritchie & Roser, 2020) (see Appendix for model regions)

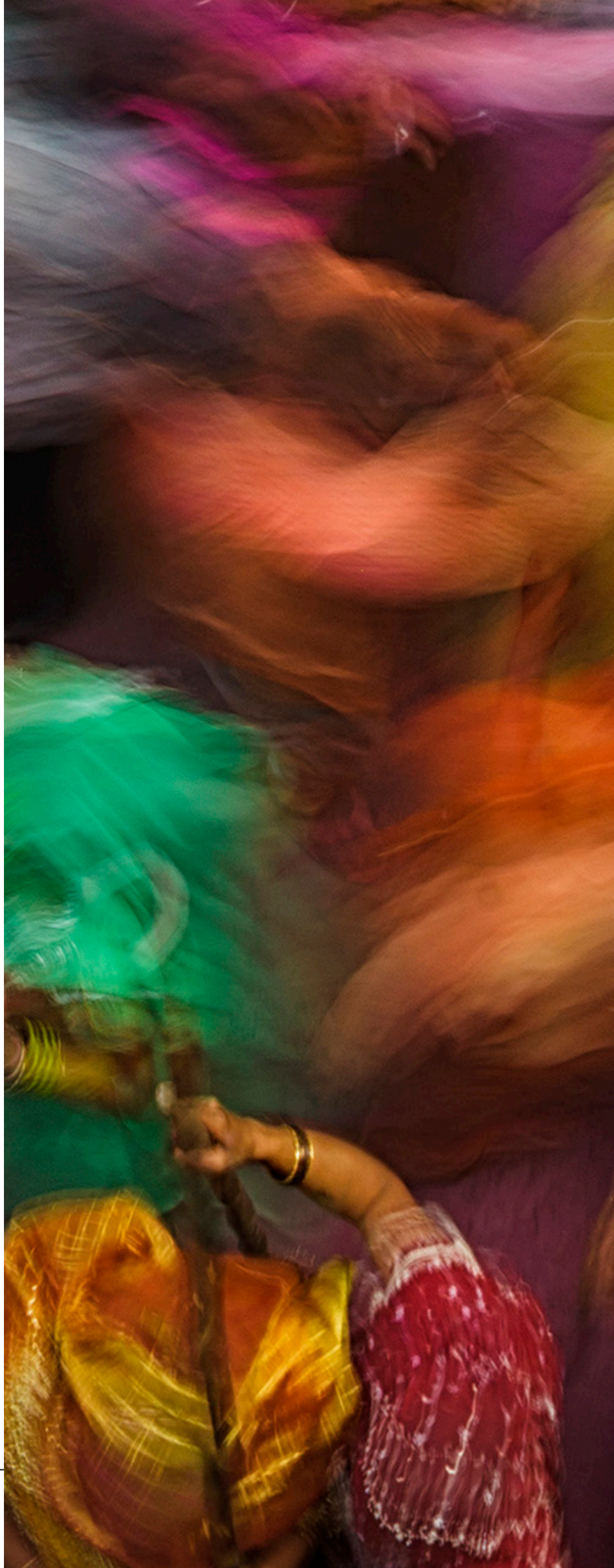
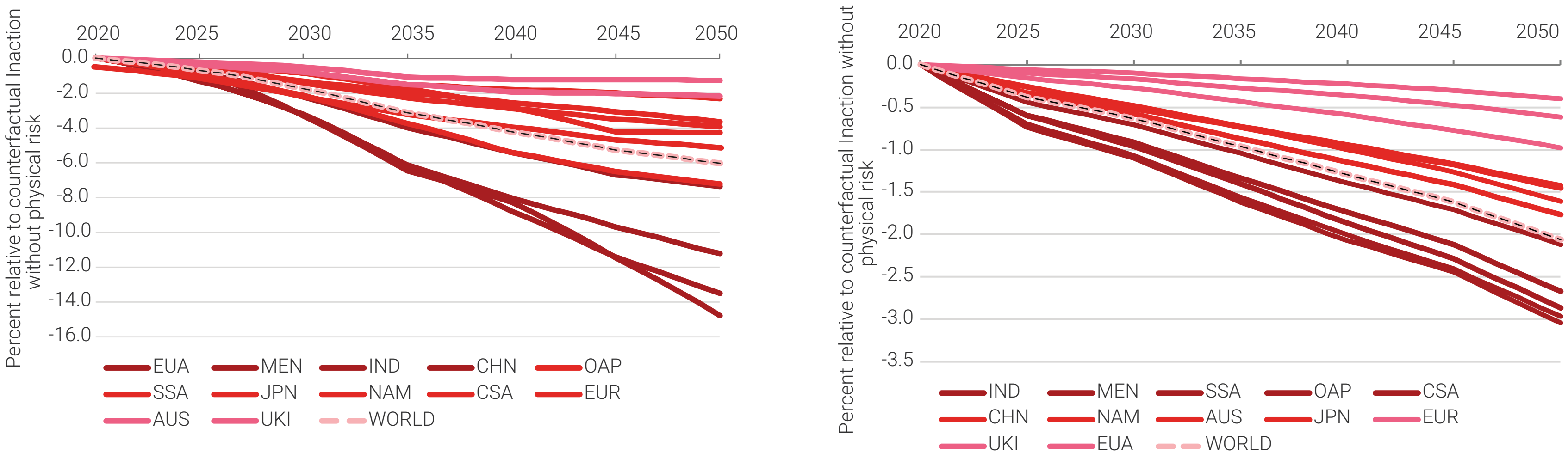


Figure 13: GDP risk by region in the net zero 1.5°C and Inaction scenarios, relative to world average



Source: LGIM Destination@Risk (see Appendix for model regions)

As the chart above shows, GDP risks from our Inaction scenario look small compared to those associated with our 1.5°C scenario, highlighting the limitations of physical risk modeling rather than signaling climate action is unnecessary. This is one of the greatest communication challenges around the climate crisis. We believe the difference in risk between our scenarios is a result of the following factors:

Time horizon

Our modeling horizon is 2050, but the worst physical risks are likely to manifest in the latter half of the century and beyond. Yet even if we knew these long-term impacts today, standard discounting practices would make them appear very small. Transition risks, by contrast, are frontloaded in the first half of the century and hence appear comparatively large

Scope

The physical risk captured in our analysis is the impact of higher temperatures on labor productivity, a type of chronic risk (physical risk from changes to the climate). This means it does not include acute physical risk from weather events such as tropical cyclones and heat waves, which are likely to become more frequent and more severe under unabated climate change. Estimates we have seen of the impacts of acute physical risks on asset values and economic output to 2050 have been small, partially because we have not yet found a methodology that goes beyond capturing the direct impacts of events – the business interruption from a factory being flooded, for example – to the wider supply chain impacts. The wealth of data required for such an exercise would be immense, but in its absence, we do not find acute physical risk estimates meaningful to include

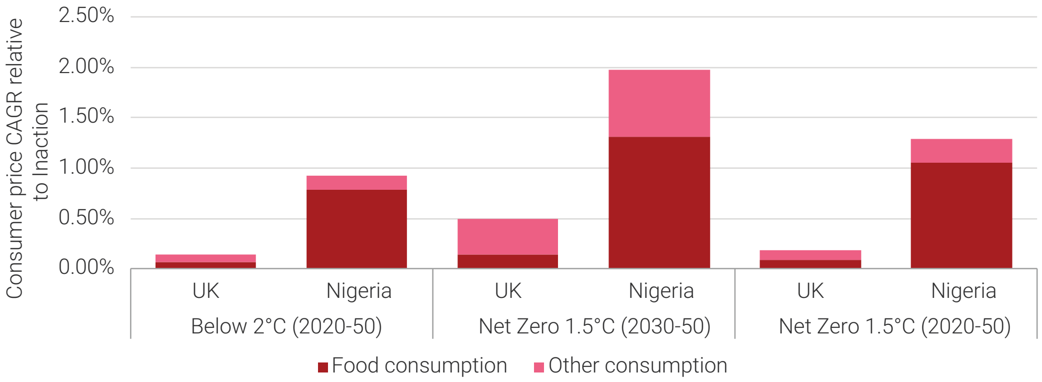
Measure

We measure physical risk in terms of impact on GDP. This means we cannot capture the impact of changes to the climate on variables that are not represented in GDP, but are nevertheless critical to economic and social prosperity, such as health, social mobility, strength of political systems, informal economies, and biodiversity

Inequality

Inequality in economic impacts is pervasive not just across countries, as shown above, but also within countries. In addition to emerging economies likely being the worst hit by the physical risks from climate change, the poorest peoples within those countries are further likely to be worst prepared for and impacted by the risks. They are most likely to live on and off land that is fragile, in settlements with little resilience to impacts

Figure 14: Consumer price CAGR relative to the inaction scenario, by type of consumption[15]



Source: LGIM Destination@Risk (see Appendix for model regions)

In addition to higher GDP impacts, emerging economies will also experience higher consumer price inflation than developed economies. Our measure of consumer inflation incorporates the effects of carbon pricing and food price increases and provides a measure of price pressures in the absence of monetary or fiscal policy response. The picture that emerges shows poorer countries especially vulnerable to food price changes, and higher consumption price inflation overall.

The chart left compares real consumer price inflation in our three decarbonization scenarios for the UK and Nigeria, disaggregating between the contribution from food and other consumption. While the two countries see similar increases in prices for non-food consumption within each scenario, once food price pressure is added, their fates diverge considerably. Today, Nigerian households spend around 60% of their expenditure on food, compared to less than 10% in the UK (USDA, 2022). This means they are much more exposed to volatile food prices in terms of their overall consumption spending. The conclusion extends beyond these two countries to a general divide between emerging and developed regions, as households with lower total consumption expenditure tend to spend a higher share of it on food.

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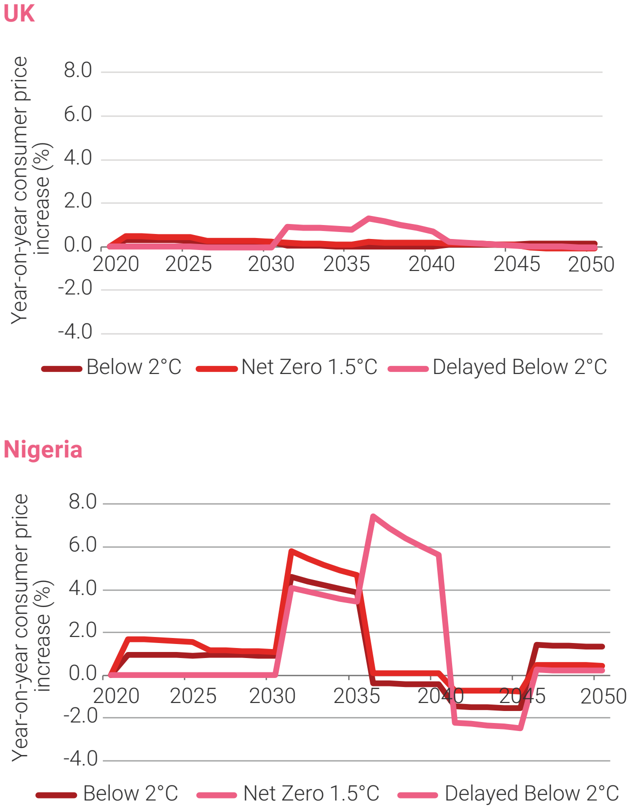
[15] Note this chart shows inflationary pressure for each scenario over the period where carbon pricing is in effect

While overall inflationary pressure may look moderate based on the chart on page 40, annual figures show considerable volatility that is obscured by the whole-period price CAGR. The delayed scenario, after the ten-year delay in policy action, sees carbon prices rise sharply in the decade after 2030. This creates significant upward pressure on consumption prices. Once price hikes become smaller, this pressure subsides and there may even be some deflation. The point here is not to try to forecast inflation – this is difficult enough on a one-year time horizon, let alone three decades – but to warn that sudden increases in carbon prices could lead to significant impacts on consumer prices and disproportionately affect the poorest consumers.

Figure 15: Consumer price change year on year, UK and Nigeria



Source: LGIM Destination@Risk (see Appendix for model regions)

Conclusions

The **future** may not resemble the past and the road **ahead** **may be** very **bumpy**!

Strap in

Ever since LGIM started working on climate analysis, one primary conclusion has stood out more than any other: the sooner we start, the easier the journey. When we first quantified this, we were confident that policymakers had ample room to maneuverer and there was good reason to be optimistic about the best climate outcomes still being highly feasible to achieve. Unfortunately, as this paper demonstrates, our initial optimism is increasingly looking misplaced. A huge range of factors have moved in favour of climate success – costs continue to fall rapidly, technology change continues to accelerate, investor awareness has dramatically increased and stated ambitions have, if anything, grown. But none of this has been matched by the capital allocation or policy action that would be required to be confident we are objectively on track for a net zero 2050 world. The one biggest policy lever – that we believe stands several orders of magnitudes above every other – to drive real change remains largely unused: the world still lacks an effective, transparent, consistently applied and above all significant price on emissions that would allow price signals to drive the market-led solution to this crisis.

The first implication this 'must have' for investors is that we need to strap in. If the world is not going to take the path of a market-led, timely transition to a net zero world, then we need to start preparing for the implications. What are some of the probable challenges that lie ahead? We think there are at least three.

Firstly, inflationary pressures are likely to build and that they may be more sustained. To be clear, the inflation we see around us today is not primarily a function of the energy transition, but likely driven by the uncertainty that the future transition is causing. A delayed transition will almost certainly lead to a sustained building of inflationary pressures and may start to materialize just as the current wave of energy price led inflation starts to recede.

Secondly, this current period of elevated volatility is likely to persist and may over time worsen. As the fundamental inequity of a delayed transition starts to manifest, with emerging market populations starting to experience both the start of serious physical climate risks (which they are likely to experience before those in developed markets), and the economic consequences of a delayed transition, the geopolitical consequences are likely to be significant. Politicians may look to raise trade barriers in response and mass migration is a real possibility. These and other risks, such as new inequalities within countries leading to social unrest and political instability, and rapid loss of jobs, mean that a transition not regarded as just could itself be threatened.

Thirdly, market returns are likely to disappoint. The unavoidable corollary to delayed action – and the significant financial risks we have attempted to quantify in this paper – is that the sum of increased volatility, lower corporate profitability, greater geopolitical risk, significant and sustained inflationary pressures and negative productivity impacts in our view all add up to lower, and probably significantly lower, market returns over the next 15 years.

Investors, we think, need to strap in. The future may not resemble the past and the road ahead may be very bumpy!

Shift gears

Investor awareness of the challenges and opportunities created by the energy transition has substantially increased over the past five years. High-carbon sectors like energy and mining are simultaneously the part of investors' holdings that contribute most to their financed emissions and critical parts of a successful energy transition that will require large amounts of capital to shift to low carbon technologies and products. Simply divesting from an investors' most polluting companies is unlikely to provide a satisfying solution to both problems if universally applied. Holdings in high-carbon sectors are not all created equal simply because they produce high emissions today. In fact, these companies are presented with an opportunity to play a leading role in decoupling economic growth from carbon emissions – and whether they chose to do so is a major distinguishing factor. Investors can help them realize this opportunity, by providing capital to those that credibly align their strategic direction with a Paris-aligned pathway. Where laggards are identified or expectations are not realized, engagement, sanctions and – where consistent with client objectives – exclusions, can be effective and meaningful tools. However, focus now needs to shift to considering what, where, why and crucially how much capital investors could be allocating to those companies that may not yet be perfectly positioned for the transition (given so very few are today) but which have the potential to be. We think investors need to consider shifting gears – to change from 'not this' to 'yes that'.

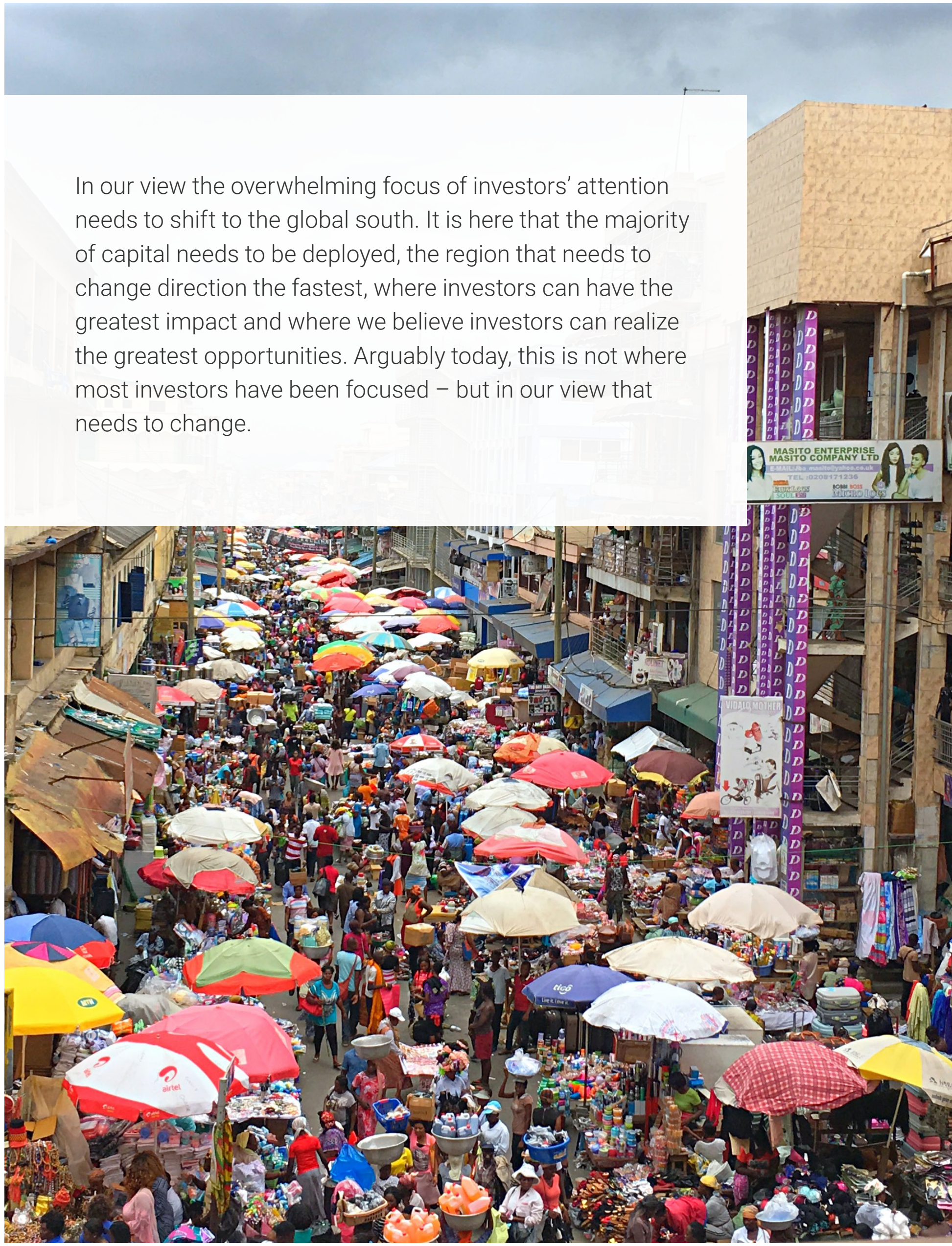
Head south

Our research tells us that the climate crisis will be won or lost, almost exclusively in the group of countries that is sometimes referred to as the 'global south' – or more generically emerging markets. In particular China, India and Sub-Saharan Africa are – we have concluded– the three places in the world that will, more than any other, determine the climate outcome that the world realizes. These three regions share three things in common.

Firstly, they have historically been responsible – as we have demonstrated above – for far less than a 'fair share' of the world's historic carbon budget. Their combined historic emissions per capita account for less than 10% of those of the UK for example[16]

Secondly, they are collectively amongst, if not the, most significantly negatively impacted from the financial and human consequences of the climate crisis. South Asia in particular, home to around a fifth of the world's population, is highly exposed to risk from physical climate change, including heat waves. Should emissions continue to grow, temperatures would likely exceed human survivability thresholds in a few densely populated locations by the end of the century (Im, Pal, & Eltahir, 2017)

Thirdly and in our view, most importantly, what they do with their energy systems over the next 15 years will dwarf the actions taken in the global north. To put this figure in context, if per capita emissions in India were to rise to the level of emissions per capita in China today, this would be equivalent to offsetting all of the decarbonization activity we forecast will take place in both Europe and North America in our Below 2°C scenario between now and 2050



In our view the overwhelming focus of investors' attention needs to shift to the global south. It is here that the majority of capital needs to be deployed, the region that needs to change direction the fastest, where investors can have the greatest impact and where we believe investors can realize the greatest opportunities. Arguably today, this is not where most investors have been focused – but in our view that needs to change.

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[16] In terms of cumulative CO2 emissions since 1800 (Ritchie & Roser, 2020) divided by current (2021) population (World Bank, 2022)

Adapt

Finally, and we make this point with some trepidation, we believe investors need to think deeply on climate adaption and how they can invest in it and protect themselves with it. Adaption is a broad term – it can mean anything from retrofitting buildings, anticipating physical risks and isolating key vulnerabilities in a portfolio, through to direct capital allocation to companies that have the potential to deliver adaptive technological solutions to some of the worst of the physical challenges that lie ahead. Institutional adaption is also going to be crucial in the years ahead in our view – and assessing and understanding the resilience of political and judicial institutions in the countries in which we allocate capital may well be crucial as the geopolitical stresses start to increase. To date investor focus on adaption has been extremely limited – and we believe that this needs to change. The road ahead, despite our collective hopes, looks to be a very bumpy one – and along with preparing for the journey investors need to think carefully about how to adapt to the destination – one which may well not be the destination we had all hoped we were heading for.

> To date investor **focus** on **adaption** has been extremely **limited** – and we believe that this **needs** to **change**.

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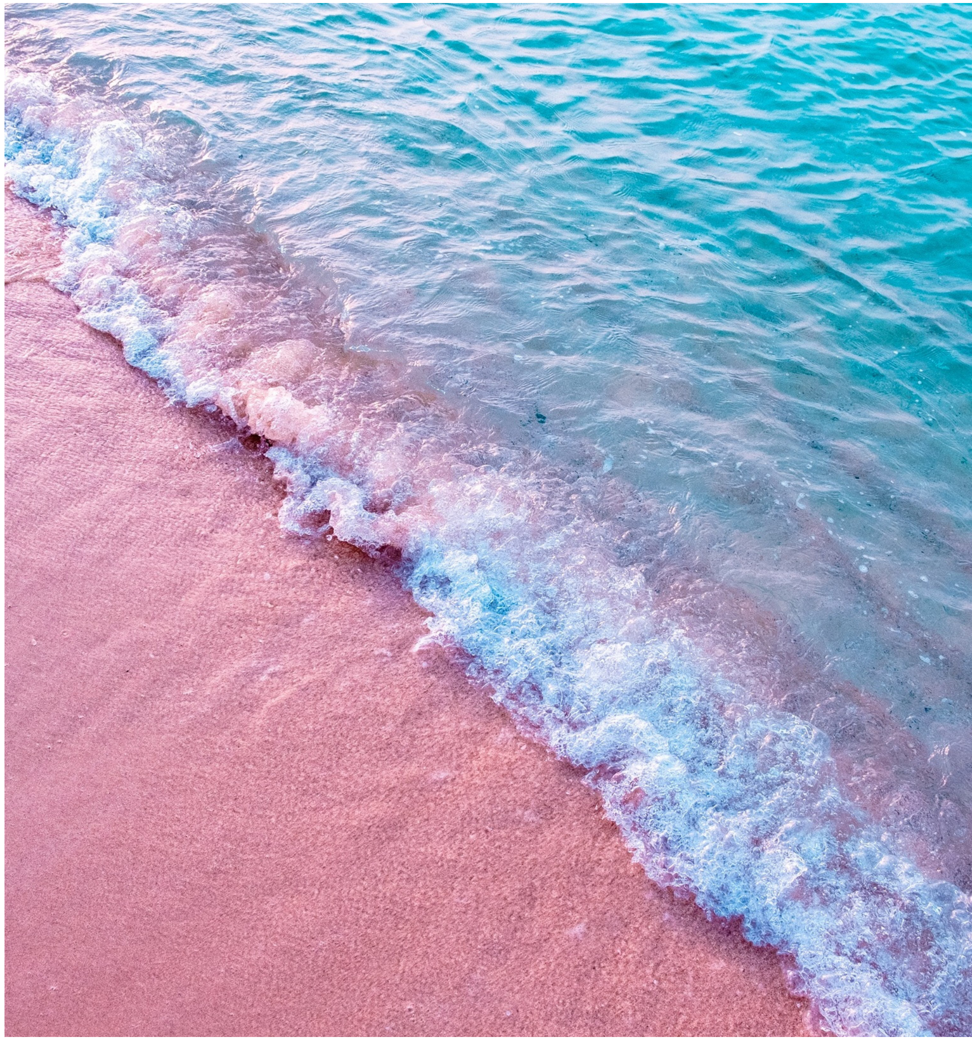
Appendix

Model regions

Abbreviation	Coverage
AUS	Australia and New Zealand
CHN	China
CSA	Central and South America
EUA	Eurasia
EUR	Europe
IND	India
JPN	Japan and South Korea
MEN	Middle East and North Africa
NAM	North America
OAP	Other Asia Pacific
SSA	Sub-Saharan Africa
UKI	United Kingdom



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