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Asset Management

Climate change and Emerging Markets after Covid-19

2020

IN PARTNERSHIP WITH

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UNIVERSITY OF OXFORD

REPORT PREPARED FOR

PICTET
Asset Management

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Foreword

The world stands to lose nearly half of its potential economic output by the end of the century. That's the shortfall we face if we fail to make further progress on climate change.

But this is only an average. Emerging markets are at risk of faring even worse given their particular vulnerabilities to rising sea levels, drought and slumps in agricultural output.

It's a bleak picture. But there are also reasons for hope.

The scientific consensus on climate change is becoming widely accepted, and governments, individuals and businesses have started to act. With the benefit of some clear thinking and careful planning, much more can be done. Particularly across the emerging world.

Everywhere, human ingenuity, technological advances and the understanding that comes from experience and education are all positive forces that will drive efforts to mitigate climate change and help us adapt to its effects.

This paper by Professor Cameron Hepburn and his team at the University of Oxford Smith School of Enterprise and the Environment offers a deep and broad analysis of the risks and opportunities emerging economies – and the world more generally – face from climate change. Their insights are based on the latest economic and climate modelling techniques.

It is research we at Pictet Asset Management are proud to have sponsored. The dynamics this report describes will play a critical role for investors over the coming decades. The pace at which governments act will determine how capital should best be allocated, be it regionally or across asset classes.

Our responsibility as managers of our clients' assets is to understand the forces that shape our world, not just during the coming quarter or two, but sometimes over lifetimes – indeed, this frames our pioneering thematic approach. It also underpins our commitment to investing in emerging markets, which, notwithstanding short-term fluctuations, represent the greatest potential for long-term economic growth. Just think of the enormous strides these countries have made over recent decades.

LAURENT RAMSEY,
MANAGING PARTNER
AND CO-CHIEF
EXECUTIVE OFFICER

Such are the foundations on which Pictet has grown during the past two centuries. But as talented as our own analysts, economists and investment managers are, we recognise there is always more to learn. For nearly a millennium, Oxford's academic community has created a well of knowledge that has profoundly influenced the course of humanity. Our own history suggests that we have also had some success in taking the long-term view.

Which is why we have forged this partnership with Oxford's Smith School. Thanks to their vast expertise in both environmental economics and emerging economies, Professor Hepburn and his team have produced insights here that aren't available anywhere else. And, extraordinarily, they've done so through the lens of one of the most traumatic global developments in modern memory.

Compounding the challenge of how to negotiate the long-term peril presented by climate change is a more immediate crisis – the Covid-19 pandemic that has ravaged communities around the world. As this paper makes clear, the vast fiscal and monetary packages governments continue to put in place to support their economies over the near term can also considerably help efforts to limit global warming over decades to come if invested wisely.

Thankfully, the worst-case outcome, that of failing to do anything more to prevent global warming than we already have, is unlikely. Governments, businesses and individuals have recognised the need for action and have put steps in place.

Rather, the issue is: how much do we do? We can't take for granted that all the effort will come from the developed world. Emerging countries are at risk of suffering disproportionately from the effects of global warming. And I think they are rising to the challenge – not least because taking measures is an investment that will often reap considerable rewards, and not just over the very long term.

In some areas, emerging economies are even well placed to take a lead. China already accounts for the lion's share of photovoltaic cell manufacturing, is at the forefront of research and development and is one of the biggest adopters of the technology. Renewables combined with decentralised energy systems could help other emerging economies escape the need for massive investment in large networks. And as renewables become ever more cost effective, many of these countries could end up with cheaper energy than their developed rivals.

Some of the measures governments introduce, such as redirecting fossil fuel subsidies towards renewable energy sources, will be temporarily unpopular because they run counter to embedded interests. But the economic justification is clear. As the cost of power generated by renewables falls, fossil fuels will become ever less attractive. Great swathes of infrastructure devoted to fossil fuel production and use will be mothballed.

Ultimately, the work done by Professor Hepburn and his team leaves us hopeful. The challenges posed by climate change are huge. But they're not insurmountable. And the emerging world has both its role to play and rewards to reap.

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Overview

As this report was being completed in July 2020, governments worldwide struggled to contain the Covid-19 pandemic while also keeping their economies afloat. Non-essential economic activity in major emerging market economies ground to a halt as waves of severe lockdowns were imposed. Significant economic rescue packages running into the trillions of dollars were launched worldwide, with the prospect of yet more to come.

The pandemic struck at a time of rising awareness of the threat posed by climate change. These concurrent crises – one immediate, the other very long term – confront governments, companies, and individuals both with enormous challenges and unique opportunities. Must these vast rescue packages perpetuate the carbon-dependent status quo? Or can they be used to mitigate what is increasingly acknowledged to be a global climate emergency? Innovative and ambitious approaches could help government bailouts of currently carbon-intensive industries, such as aviation, and also make them cleaner and greener.

Emerging market economies cannot be passive observers in these deliberations. Accounting for half the world's output, much of its population, and with the greatest potential for economic growth, these countries are a crucial component in how and to what degree the world moves away from carbon dependence after Covid-19.

Before the pandemic, countries were ramping up action against climate change. International negotiations in Paris in 2015 led to the global agreement that emissions need to reach net zero by the second half of the century, and that countries should endeavour to limit warming to "well below" a 2°C rise from pre-industrial levels. The cost of renewables has gone down substantially, and fossil fuel investments have become much riskier. Business and financial actors are seriously considering their exposure to climate change risks.[1]

1 McKinsey Global Institute, 2020. Climate Risk and Response: Physical Hazards and Socio-economic Impacts.

This report focuses on the role emerging market countries will likely play in the lead up to the climate conference (COP26) in 2021. Our analysis is relevant to two key questions they face:

— Should emerging market economies more actively push for climate action?
— If so, how should they seek to accelerate the low-carbon transition?

— The report provides an up-to-date analysis of the significant threats to and opportunities for emerging market economies from climate action and from climate impacts, along with an analysis of the growing opportunities for investors to participate effectively in the low-carbon transition in emerging markets. We find that there are ever more ways in which climate action in emerging markets can enhance prosperity in almost all key sectors in these economies.

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Executive Summary

The Covid-19 pandemic has upended the world economy. Strict lockdown measures have put certain carbon-intensive sectors such as aviation and transportation under financial duress. The extraordinary decline in oil prices has underscored the importance of investing in flexible assets. Oil fields, once in operation, cannot quickly be "switched off", a fact that pushed prices in the oil futures market into negative territory for the first time in history. In these unprecedented times when governments are announcing large stimulus packages to revive their economies from the Covid-19 pandemic, there is a unique opportunity to build back better through investment in sustainable projects.

The decisions of the coming months will be essential to safeguard our planet. Only a substantial change in practices will allow governments, businesses, and citizens around the world to efficiently curb climate change.

Unfortunately, progress on climate change over the last decade has been inadequate. Already, temperatures have risen by more than 1°C since 1880[2], and projections suggest that under currently stated policies, the surface of the Earth could be warmer by 2.8°C by the end of the 21st century, compared to pre-industrial temperatures (see section 1.2).

Impacts and risks for emerging market economies are larger than for high-income countries. Building on a set of scenarios employed by the Intergovernmental Panel on Climate Change (IPCC), called the "shared socioeconomic pathways" (SSP), we find that unmitigated climate change could reduce the world GDP per capita some 45 per cent by 2100 compared to a scenario without further climate change. Depending on population and economic growth assumptions, these damages could equate to somewhere from USD90 trillion to more than USD500 trillion by 2100. A scenario based upon "current policies" is likely to result in at least USD200 trillion in damages by 2100.[3] Although these estimates may appear very large, they could well be a significant underestimate of actual damages, due to certain inherent limitations associated with our analysis.[4]

2 NASA World of Change webpage (https://earthobservatory.nasa.gov/world-of-change/decadaltemp.php). Accessed on 20th March 2020.

3 Absolute GDP impact estimates are presented in 2020 US dollar purchasing power parity (PPP). The range is based on the minimum and maximum from the different possible socioeconomic pathways examined. The full range of damages across all scenarios and pathways, along with discussion of the methodology, is provided in the Appendix.

4 Although our methodology is unusually grounded in empirical evidence, such a data-driven analysis (indeed any analysis) can only go so far when projecting into the distant future beyond many potential structural breaks. The credibility of the results will decline the further temperatures increase beyond current experience, so our confidence is lowest in the worst-case estimates. Furthermore, our analysis does not account for the systemic impacts that economic declines in the global economy will have on individual economies through declines in trade. The impacts of climate change could therefore be even more severe than modelled in this analysis.

Despite fundamental uncertainties, we can be confident that emerging market economies' current high growth rates would be stunted by severe climate change disruptions. India, like many emerging economies in latitudes that are already warm, will suffer more from climate change than countries in more temperate regions.[5] Furthermore, agriculture will suffer from changes in temperature and rainfall patterns, which is a major concern for emerging economies, given that sector still accounts for a significant share of their GDP and employment. Finally, the world's most vulnerable populations live in emerging economies and are thus less likely to have the means to protect themselves against the negative impacts of climate change. GDP losses in key emerging market economies such as India are likely to exceed global averages (see Fig. 1, panel a).

Limiting warming to "well below 2°C", as agreed in Paris, requires reducing greenhouse gas emissions by about 50 per cent in the next decade. What's more, to achieve the goals of the Paris Agreement and prevent the most catastrophic effects of further warming, global greenhouse gas emissions will have to reach net-zero by the middle of the century.[6] In the previous decades, efforts have been too slow, leaving the world heavily reliant on fossil fuels. The fossil fuel infrastructure currently available around the world is so large that its use at full capacity in the next 20 years would already commit the planet to at least 1.5°C degree warming.[7] This infrastructure amounts to two-thirds of the available emissions until 2100 if we want to remain below the 2°C target (see Fig. 1, panel b). Yet new capacity is being built by investors who are probably significantly underestimating the risks they are taking. Limiting warming to well below 2°C will require keeping oil, gas and coal in the ground, as well as decommissioning some of the existing infrastructure built to extract and process fossil fuels (see section 3.3). This problem is a major issue in emerging economies, especially in China and in India, because of their heavy reliance on coal.

5 Burke, M., Hsiang, S. M., & Miguel, E. (2015). Global non-linear effect of temperature on economic production. Nature, 527(7577), 235-239.

6 IPCC (2018). Summary for Policymakers. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. World Meteorological Organization, Geneva, Switzerland, 32 pp. and see the 'high-ambition' scenario modelled below (see section 1.2)

7 Tong, D. et al. (2019). Committed Emissions from Existing Energy Infrastructure Jeopardize 1.5 °C Climate Target. Nature 572(7769): 373–77; Pfeiffer, A., Millar, R., Hepburn, C., & Beinhocker, E. (2016). The '2 C capital stock' for electricity generation: Committed cumulative carbon emissions from the electricity generation sector and the transition to a green economy. Applied Energy, 179, 1395-1408 and Pfeiffer, A., Hepburn, C., Vogt-Schilb, A., & Caldecott, B. (2018). Committed emissions from existing and planned power plants and asset stranding required to meet the Paris Agreement. Environmental Research Letters, 13(5), 054019.

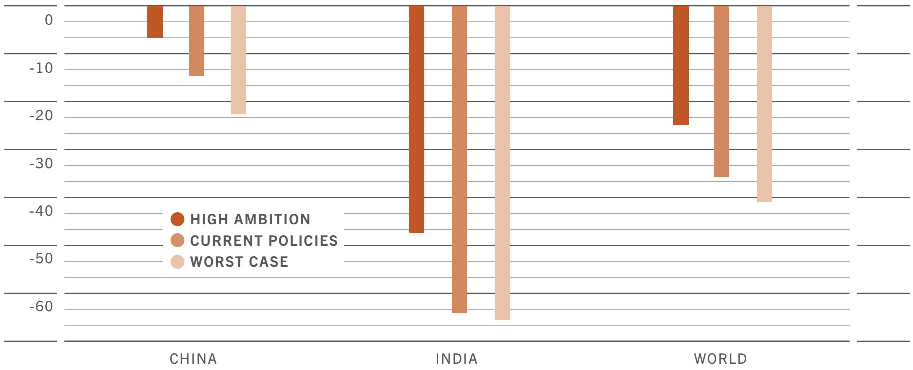
FIG.1

GLOBAL CHALLENGES AND OPPORTUNITIES IN THE LOW-CARBON TRANSITION

FIG.1A

Estimated impacts of global warming by 2100 on China, India and the world for three climate change scenarios

GDP PER CAPITA IMPACTS BY 2100*
LEVEL GDP PER CAPITA DIFFERENCE TO SSP2



* Results based on historical economic-metric estimates and projected using cmip5 climate models. Results show the mean difference to a baseline scenario (ssp) without climate impacts

FIG.1B

Global committed emissions from Energy and Industry infrastructure (lighter colours) compared to emissions allowed in the 'high-ambition' scenario (dark orange)

COMMITTED ANNUAL CO_2 EMISSIONS, GT CO_2 PER YEAR
SCENARIO EMISSIONS ENCOMPASS ENERGY AND INDUSTRIAL PROCESSES
COMMITTED EMISSIONS

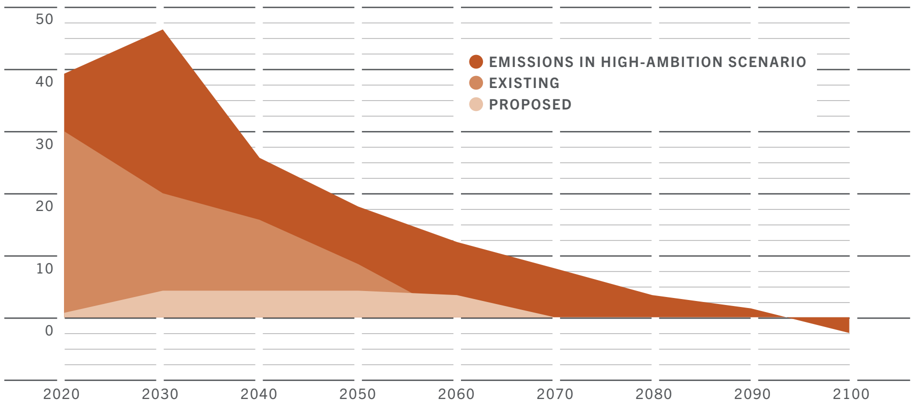
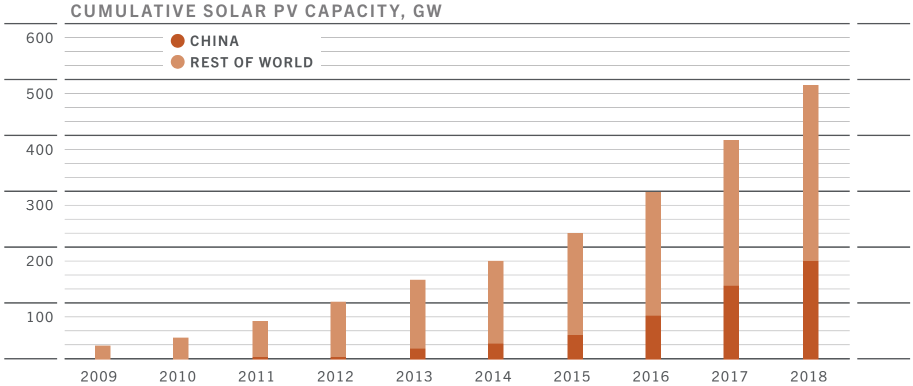


FIG.1C

Cumulative Solar PV capacity for China and the rest of the world

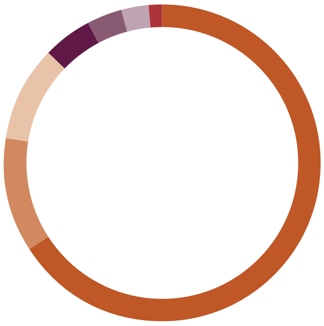
CUMULATIVE SOLAR PV CAPACITY, GW



Investment in climate-related finance since 2004

FIG.1D

CLIMATE-SMART INVESTMENT POTENTIAL 2016-2030
TOTAL = USD22.633 TRN



Source: Sources: a) this report b) reproduced from Tong et al. (2019) and Huppmann et al. (2019), c) BP Statistical Review (2019) and d) Climate Finance Leadership Initiative (2019).
Note that in panel (a) for India, damages under 'current policies' are higher than in a 'worst-case' scenario. This illustrates the low confidence in damage estimates so far from current experience. Our more detailed modelling (not shown here) displays a trend of greater damages for India at higher temperatures, as expected. However, variability in damage estimates is large; confidence is particularly low in the 'worst-case' estimates, and confidence intervals large, such that the difference between the 'current policies' and the 'worst case' for India is not significant. In practice, omitted factors mean that we would expect the 'worst case' to involve larger damages than 'current policies'.

Even though hugely ambitious, the required global reduction in emissions is not impossible:

— The pandemic may provide a window of opportunity to redirect government expenditure to green sectors. With large sums being galvanised to stimulate the economy during the pandemic, there is an opportunity to leverage this money to fund green industries with high economic multipliers. A challenge is that many emerging markets are using these funds to finance carbon-intensive sectors. National governments may, however, be able to re-orient this expenditure or attach green conditionalities to the support given to carbon-intensive sectors.

— Emerging countries have furthermore realised that the threat posed by climate change is too serious for inaction to prevail. The country-level analysis in section 1.2 suggests that, in some areas, the impact from climate change will be so severe that inaction is not a viable option. Impacts tend to concentrate on key sectors, such as agriculture and power, that provide essential goods to support livelihoods (see section 1.3). Ten years ago, very few emerging economies had made commitments towards reducing greenhouse gas emissions. The Paris Agreement has opened the way to new flexible discussions in which all countries, rich and poor, are developing and updating their nationally determined contributions to fight climate change.

— Low-carbon technologies have continued to fall in costs and emerging markets have seized the opportunity to become the largest suppliers. Solar photovoltaics show clearly that investment in emerging market renewable energy has the potential to provide large returns. The cost of solar photovoltaics has been consistently dropping by around 10 per cent per year on average over the past four decades,[8] meaning a solar panel now costs approximately 30 per cent of what it cost in 2010, and roughly 10 per cent of what it cost in 2000. The drastic reduction in the cost of solar PV has allowed its rapid expansion, and similar trends are observed for other low-carbon technologies, such as wind or Lithium-ion (Li-ion) batteries. As foreshadowed in the report by the Emerging Markets Forum in 2010, China has since captured much of the growing solar market, becoming, in less than a decade, the main supplier of solar panels (see Fig. 1, panel c). China's share of global solar manufacturing grew from about 1 per cent in 2001 to about two-thirds of the supply today. This is a clear example of how emerging markets can successfully engage in the transition to a low-carbon economy. For now, limits to the development of renewables still exist, especially since renewables are intermittent (they depend on wind and sun availability) and not all economic sectors can be easily electrified. However, technologies are evolving rapidly. For instance, storage technologies necessary to overcome intermittency issues are also falling rapidly in cost. In addition to declining costs of batteries, it now seems very likely that hydrogen and ammonia will become cost-competitive renewable energy vectors.
— Green finance has been booming, and emerging markets will offer strong investment opportunities. Sustainable assets are now estimated to be worth more than USD30 trillion,[9] a figure that is growing fast, especially in emerging economies. Between 2016 and 2030, the International Finance Corporation estimates that there will be USD22 trillion worth of climate-smart investment opportunities, with China accounting for more than 65 per cent of this amount – some USD14 trillion (see Fig. 1, panel d).[10] All major sectors ranging from industry to agriculture require low-carbon financing. The power sector needs a sixfold increase in investment by 2050 (relative to 2015) to limit warming to

8 Farmer and Lafond (2016), Farmer, J. D., & Lafond, F. (2016). How predictable is technological progress? Research Policy, 45(3), 647-665.
9 Global Sustainable Investment Alliance (2018). 2018 Global Sustainable Investment Review.
10 International Finance Corporation (member of the World Bank Group) (2016). Climate Investment Opportunities in Emerging Markets: An IFC Analysis. Washington D.C., United States.

1.5°C.[11] Likewise, sectors such as cement, aluminium, iron and steel need to undergo radical transformations to meet the net-zero target. In parallel, the required capital to finance the transition exists. Today, coal, oil and gas receive more than USD370 billion per year in public support, compared with USD100 billion for renewables.[12] Public support is already being diverted from fossil fuels to renewable energy and could contribute significantly to paying for the global transition to clean energy.[13] With a growing population, growing energy demand and growing economies, emerging markets will offer unprecedented opportunities for green investments. In the green transition post Covid-19, investors might be well advised to ask the following questions:

1. ***Are returns commensurable with risks of fossil investment?*** Fossil fuel assets are risky. Returns should be assessed against the risks that they entail in the future. The recent collapse in the oil price to as low as USD25 per barrel, and negative in oil futures, provides an illustration of the risks in the sector. As discussed in this report, the risks to fossil fuel assets include stranding, lower utilisation rates, climate policy and litigation. For the same level of profitability, low-carbon technologies are likely to be a much safer bet.
2. ***Do investee companies understand and disclose their climate change exposure?*** Investors should know about the risks they take. The implications that climate change could have on a business can be extremely complex – there will be opportunities as well as risks with many risks indirect, and some systemic.
3. ***Which emerging market countries have a coherent low-carbon transition plan?*** Countries that do not plan for the low-carbon transition are taking big risks, too. They are not favouring the commercial and industrial environment that will be resilient to climate disruptions. They could potentially be locking themselves in technologies that will be outdated and, eventually, stranded. When investors decide to divest from fossil fuels, pollution havens could suffer from a collapse in foreign direct investment and be exposed to severe macroeconomic disruptions.

11 IPCC (2018) Special Report: Global Warming of 1.5 degrees Celsius: Summary for Policymakers, Geneva, Switzerland.
12 IISD and GSI (2019) Fossil Fuel to Clean Energy Subsidy Swaps: How to Pay for an Energy Revolution, Geneva, Switzerland.
13 Ibid.

4. ***Would portfolios yield higher long-term returns with stronger climate action?*** The economic losses from climate change could be so large that many investors, even those that have interests in assets related to fossil fuels, are likely to be better off with strong climate action than suffering the damage to their portfolios arising from inaction. This may particularly be the case with capital engaged in emerging market economies as these are likely to be more vulnerable.
5. ***Are sensible adaptation and insurance measures in place?*** Some of the negative impacts of climate change can be addressed by proper adaptation measures. While sometimes expensive, these measures tend to significantly outweigh the costs of doing nothing. Extensive risk assessments and cost benefit analyses may be required to identify the best adaptation strategies. Nature-based solutions and early warning systems are some relatively cheap ways to achieve very favourable adaptation outcomes and risk reductions. Also, insurance products constitute a valid adaptation strategy in themselves, although the insurance industry is struggling to price in the large systemic risks associated with climate change.

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Introduction

This report comes out at a critical time in history. The Covid-19 pandemic has led to an unconscionable number of deaths and has deeply disrupted the global economy. At the same time, the world is on the verge of an environmental catastrophe: the next decade will be decisive to prevent it.

Under these circumstances, this report examines the socioeconomic and strategic implications of climate change in emerging markets and the role that private finance could play in a green recovery post Covid-19. Since the Stern Review, a large body of literature has made clear the need to act on climate change as soon as possible, because delaying climate action will only increase the ultimate costs of climate change. In the aftermath of the Covid-19 shock, there is an opportunity to use the financial impulse of national recovery packages to accelerate the transition towards a low-carbon economy. The costs of past inaction are already visible: heatwaves, floods and droughts have become more frequent, with substantial impacts on economies and livelihoods. For investors, the costs of inaction are also lurking. There is too much fossil fuel infrastructure around the globe, and some will have to be stranded. It may be only a matter of time before low-carbon technologies become the most competitive option in nearly all circumstances. Both industrialised and emerging economies have an interest in deploying green industrial strategies.

This report focuses on the role that emerging markets will play in the green transition post Covid-19. It particularly focuses on the largest of these developing economies, China and India, which will be driving global change. It also provides evidence for other emerging economies, such as Brazil, Indonesia, Mexico, Russia and South Africa.

This report is structured as follows:

1. Section 1 sets out three future scenarios for the world's climate and the world's economy, depending on which groups of countries act against climate change. It also provides country-specific information (for Brazil, China, India, Indonesia, Mexico, Russia and South Africa) and evidence of sectoral impacts (for the power sector and agriculture) in the absence of successful adaptation and mitigation.
2. Section 2 looks at the current landscape of the green recovery, highlighting the current technological and political landscapes.
3. Section 3 provides a general outlook of the recent developments in green finance to accompany the green economy.
4. The Appendix provides a detailed methodology and technical information on how the global climate change impact assessments were calculated for this report.

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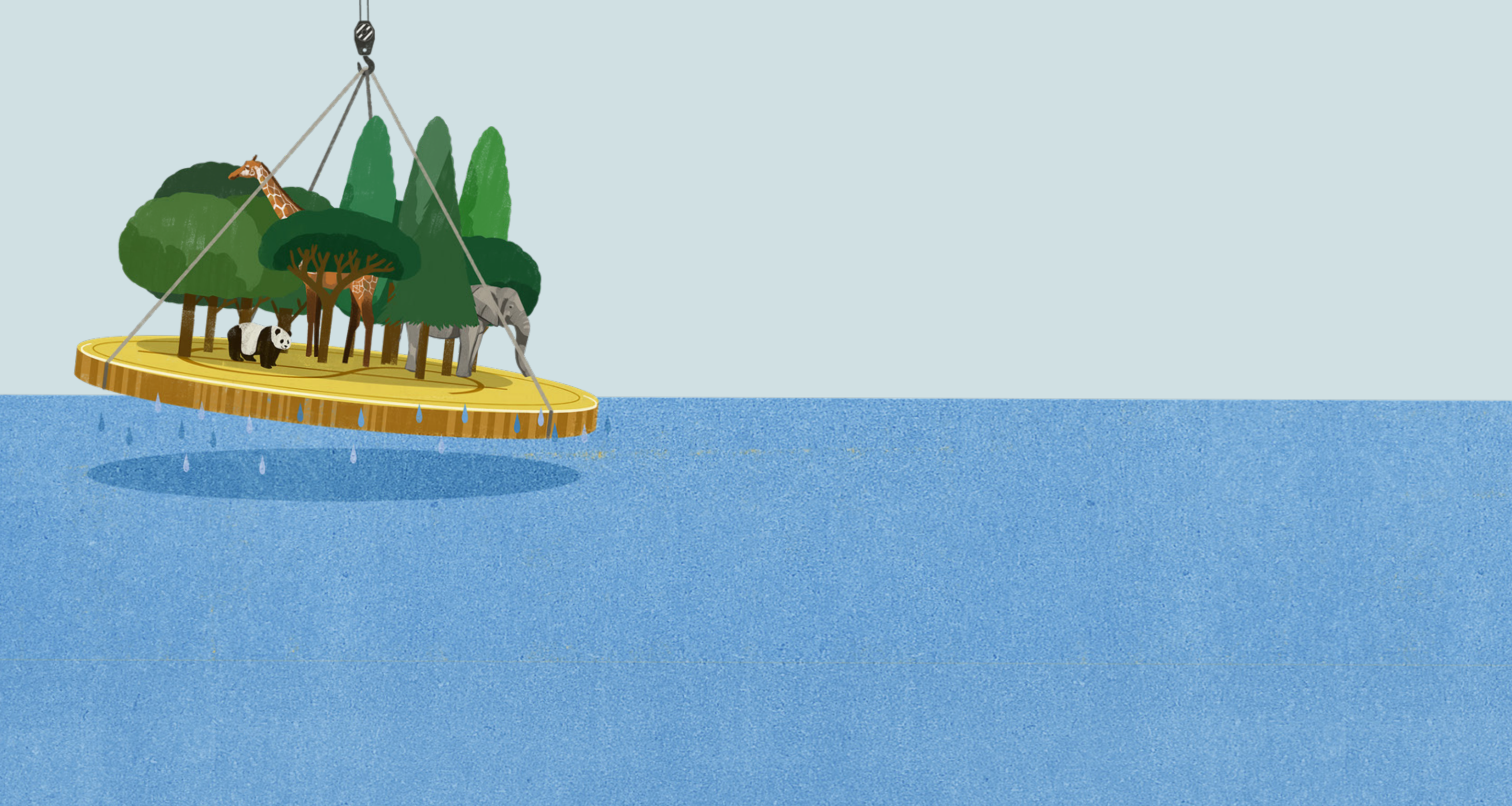
The economic and social impact of climate change on emerging markets



The economic and social impact of climate change on emerging markets

This report presents a new set of estimates for the potential global impacts of climate change, focusing primarily on emerging market economies. The analysis centres on three global warming scenarios. In the first, the 'high-ambition' scenario, governments in both the developed and developing world take concerted action on climate change and, in doing so, are effective in limiting further temperature rises. In the second, the 'current policy' scenario, current policy pledges are implemented – with developed countries doing most of the heavy lifting – leading to a relatively moderate further rise in global temperatures. And in the third 'worst-case' scenario, which also happens to be the most unrealistic, governments the world over fail to take any preventative action, leading to significant warming by the end of the century.

Although we assign no probabilities to any of these scenarios, we believe the future state is likely to fall somewhere between the first and the second.

In any event, these possible policy paths provide sufficient contrast to make clear the need for action on climate change by all countries, including those across the emerging world. And they also give an indication of the range of impacts global warming could have on the world.

This research also presents a new approach to modelling climate scenarios. It is one that we believe paints a more realistic picture of possible outcomes. Most climate models used by policymakers belong to a class known as Integrated Assessment Models (IAMs). These couple climate models with economic and land-use models to estimate the effects climatic change will have on the population, given a range of plausible trajectories for economic growth and development. Unfortunately, these models suffer from many serious problems.[14] One is that the 'damage function' — the economic cost of rising temperatures — central to these IAMs tends to depend on "arbitrary functional forms and corresponding parameter values."[15] In

14 Farmer, J. Doyne, Cameron Hepburn, Penny Mealy, and Alexander Teytelboym. 2015. "A Third Wave in the Economics of Climate Change." Environmental and Resource Economics 62(2): 329–57.

15 Pindyck, Robert S. 2017. "The Use and Misuse of Models for Climate Policy." Review of Environmental Economics and Policy 11(1): 100–114.

other words the scientific basis for temperature effects on economies is weak, in part because there has been little effort devoted to studying these relationships. This 'wicked problem'[16] is further bedevilled by the fact that each of the climatic, environmental and economic systems these models depend on is highly complex and can change continuously and in non-linear ways.

Our solution is to take some of the components of IAMs – the range of warming scenarios as well as the socioeconomic pathways that produce these scenarios – and to augment them with detailed analyses of the potential risks associated with climate change. In doing so, we attempt to make clear the uncertainty inherent in this complex problem while at the same time providing the most up-to-date analysis of potential climate change impacts.

We then complement this modelling exercise with detailed country-level evidence for China, India, Brazil, Indonesia, Mexico, Russia and South Africa, and sectoral analyses of the impacts of climate change for the power sector and agriculture.

16 Churchman, C. West. 1967. "Wicked Problems". Management Science 14(4): B-141.

1.1 Estimating climate change impacts

We begin the analysis with three global-warming scenarios that we believe give a good indication of the range of possible outcomes (a more detailed explanation of our methodology can be found in the Appendix)*.* Each of these scenarios is linked to the Representative Concentration Pathways (RCP) developed by the Intergovernmental Panel on Climate Change (IPCC). These RCPs standardise climate-economy modelling efforts by describing how different levels of greenhouse gas emissions will affect the world over the course of this century.[17] Our three scenarios are shown in Fig. 2 and are as follows:

— High-Ambition Scenario in which immediate climate action is taken by all countries, including emerging market economies, thus limiting the rise in global average temperature to 1.6°C above pre-industrial levels in 2100;
— Current Policies Scenario mostly follows current policy pledges, largely involving action by developed countries (2.8°C in 2100).
— Worst-Case Scenario with no action to mitigate global climate change (4.3°C in 2100).

The key difference between the 'worst-case' and the 'current policies' scenarios is the estimated difference between no country taking action and only developed economies making efforts – in other words, the difference is the effect of climate mitigation efforts by developed economies.[18]

We don't attribute probabilities to any of these scenarios – they merely illustrate possible paths – but in our view the outcome will probably fall somewhere between the 'current policies' and 'high-ambition' scenarios. The 'worst-case' scenario appears to us to be unlikely, given that it assumes investment in the fossil economy will continue at past rates – an assumption that is not consistent with rising rates of investment in ever more cost-competitive alternative clean energy technologies.

17 van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., … Rose, S. K. 2011. The representative concentration pathways: An overview. Climatic Change, 109, 5–31.

18 The 'current policies' scenario achieves a similar warming profile to the WITCH AMPERE3-RefP-EU model run, which models an EU-led mitigation scenario explicitly.

Onto these scenarios, we then overlay the range of "Shared Socioeconomic Pathways" (SSPs) used in the sixth Coupled Model Intercomparison Project (CMIP6). Each of the five SSPs outlines a different plausible pathway global societies and economies could take over the coming decades, each of which presents lesser or greater challenges to mitigating or adapting to climate change.[19]

It is entirely plausible that the emission levels in each of the warming scenarios we consider could result from many different combinations of socioeconomic development and climate action by different countries, which is why we use the scenario matrix approach proposed for CMIP6. Each of the SSPs represents a different plausible combination of the key sources of emissions, including population growth, economic growth, technological change, changes in demand for goods and services, land-use change, levels of international cooperation, climate mitigation ambition, and adaptation efforts. Combining the RCPs with the SSPs allows us to derive emissions and greenhouse gas concentration scenarios associated with each of the alternative socioeconomic assumptions underlying the SSPs. This approach then allows us to assess which climate policies could achieve the radiative forcing levels defined by the RCPs. Radiative forcing is a measure of how much of the sun's energy is reflected back into space and how much is absorbed – greenhouse gases increase the relative amount that the earth's atmosphere absorbs.

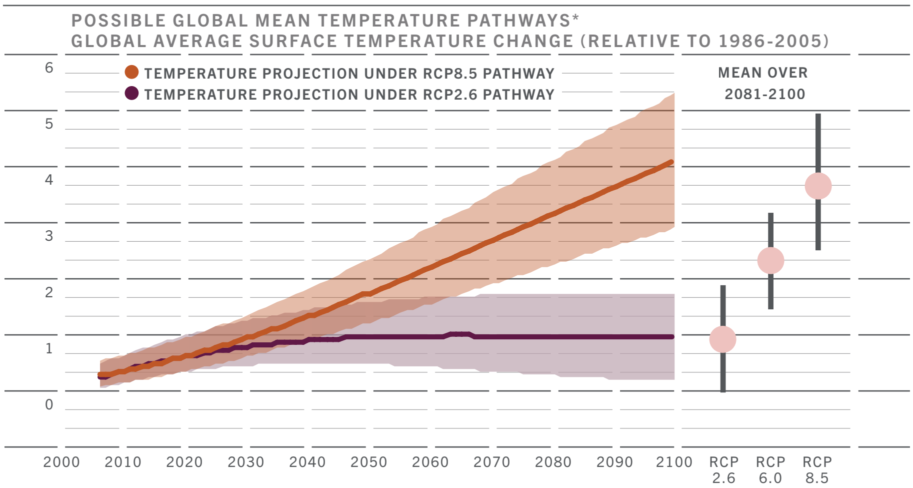
Thus, each of our scenarios consists of an underlying SSP pathway subject to different climate mitigation policies that achieve the emissions associated with each RCP warming scenario.

This combination of the three warming scenarios and five SSPs enables us to capture a wide range of possible socioeconomic and climatic futures. This mirrors an approach used in the most recent IPCC Special Report on Global Warming of 1.5°C.[20]

19 Riahi, Keywan et al. 2017. The Shared Socioeconomic Pathways and Their Energy, Land Use, and Greenhouse Gas Emissions Implications: An Overview. Global Environmental Change 42: 153–68.

20 IPCC, 2018: Summary for Policymakers. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. World Meteorological Organization, Geneva, Switzerland, 32 pp.

FIG.2



Source: Based on IPCC Synthesis Report 2014

* The mean indication over 2081-2100 was used to determine the projected temperature by the end of the century in this report. Forecast changes under IPCC global warming scenarios identified are based on the Representative Concentration Pathways (RCPs) developed for the IPCC to describe different climate futures based on different trajectories of greenhouse gas emissions

Finally, we calculate what the impact of warming would be on the global economy and environment under our various scenarios for each of the SSPs. To overcome the difficulties of estimating economic and environmental damage associated with each warming scenario, we apply, in each case, the most up-to-date published methodology consistent with this combination of warming scenarios and socioeconomic pathways. We estimate the direct economic impacts from warming – including extreme weather events (such as storms, wildfires and droughts), and changes in labour productivity and agricultural growth – in terms of gross domestic product (GDP) per capita. To complete the coverage of potential impacts, we also provide estimates of losses due to sea-level rise, to potential changes to biodiversity, and to the retirement (or 'stranding') of assets associated with ambitious climate mitigation targets (so-called transition risk). Our estimated GDP per capita impacts are presented as a contrast to the GDP per capita estimates of the various baseline SSP scenarios, which, on their own, are merely illustrative counterfactuals since they assume no climate action or climate change.

Even under our most ambitious scenario, all countries will continue to experience the physical impacts of a hotter climate. These will include damage caused by ever more powerful and/or more frequent extreme weather events including floods, hurricanes, droughts and wildfires; by a rising sea level and consequent storm surges; by reduced productivity of workers and equipment; and by changes in agricultural yields and biodiversity.[21] In some countries and regions, there are likely to be some positive

21 IPCC. 2014. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. eds. C B Field et al. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, : IPCC.

effects arising from increased warming, particularly in the northern extremities, where warming might result in increased economic activity over the year, increased availability of arable land, and increased agricultural yields for a period. See the Appendix for more details.

In the absence of effective mitigation, temperatures will continue to rise beyond 2100 and substantially alter climates across the globe, particularly in high latitudes, such as the Arctic. In all three scenarios, mean annual temperatures rise beyond current levels. In our 'worst-case' scenario, global average temperatures rise to roughly 4.3°C above pre-industrial levels, with annual mean temperatures increasing by at least 4°C above 2005 levels across a swathe of countries, including China, India, the US, and across northern Africa. Such an increase is also associated with a considerable shift in extreme weather patterns, such as heatwaves and droughts. The climatic change associated with the 'current policies' scenario is less severe than that under the 'worst-case' scenario but still results in around 2.8°C of warming above pre-industrial levels by the end of the century, with temperatures continuing to rise into the next century. The global temperature under a 'high-ambition' scenario stabilises at 1.6°C above pre-industrial levels, broadly little changed from where we are now. However, predicting or modelling rapid and irreversible changes – in other words, identifying the 'tipping point' – in any system as complex as the global climate is inherently challenging, and the best available evidence suggests negative feedback loops could be triggered even at warming levels of between just 1°C and 2°C.[22] Maps of temperature differences across the globe for each of the warming scenarios are presented in the Appendix.

Human societies will be significantly affected and disrupted. In the absence of strong mitigation action by emerging economies, we estimate that global GDP per capita will be 45 per cent[23] lower than in the absence of climate change (Table 1), based on a new empirically specified approach to damage estimation (explained below). We estimate that strong mitigation by all countries (the 'high-ambition' scenario) would reduce the impact to a 27 per cent drop (Table 1). These results represent the difference between GDP per capita with climate impacts and an

22 Lenton, T. M., Rockström, J., Gaffney, O., Rahmstorf, S., Richardson, K., Steffen, W., & Schellnhuber, H. J. (2019). Climate tipping points—too risky to bet against.

23 As detailed in the Appendix, the numbers in brackets represent the high and low estimates generated from across the five alternative future economic scenarios embodied in the shared socioeconomic pathways (SSPs)

assumed baseline without such impacts, across the full range of plausible SSPs – see Appendix for more information. The current 1°C of warming above pre-industrial levels has already altered our climate substantially; our modelling suggests that global GDP per capita will continue to be reduced by climate change in all future scenarios, including the 'high-ambition' scenario.

Our conclusions are based on modelling produced exclusively for this report, building on the methodology developed by Pretis et al.,[24] and making use of a new dataset for historical economic development and future warming. Using this approach, we derive these estimates by calibrating a model on historical impacts of inter-annual climate variations using advanced econometric methods,[25] which allows us to formulate a climate impact function. We then disaggregate this damage function to the country level and use future climate model output to estimate the overall GDP per capita impact.[26]

This modelling approach is, in our view, significantly

TABLE 1

SUMMARY OF THE ESTIMATES FOR CLIMATE IMPACTS ACROSS THE THREE PLAUSIBLE GLOBAL WARMING SCENARIOS*

	HIGH-AMBITION SCENARIO	CURRENT POLICIES SCENARIO	WORST-CASE SCENARIO
2100 GLOBAL MEAN TEMPERATURE ANOMALY RELATIVE TO CLIMATOLOGY 1850-1900	1.6°C	2.8°C	4.3°C
GLOBAL GDP PER CAPITA IMPACT (USING SSP2 AS THE CENTRAL ESTIMATE)	-27.2% [-21.4%; -27.3%]	-39.5% [-31.8%; -39.9]	-44.9%** [-36.9%; -45.7%]
ESTIMATED CUM. GDP COST OF GDP-BASED IMPACTS (USING SSP2 AS THE CENTRAL ESTIMATE)	USD 186 trn [91; 325]	USD 272 trn [137; 474]	USD 298 trn [148; 524]
TRANSITION RISK (TO EXISTING AND PLANNED ASSETS)	USD 5 TO 17 TRN	-	-
GLOBAL SEA-LEVEL RISE BY 2100	0.44 M	0.53 M	0.85 M
BIODIVERSITY IMPACT EQUIVALENT PRISTINE HABITAT LOSS	2.5 million km^2	8 million km^2	8 million km^2

* Values and ranges shown across SSP scenarios. Global GDP-based impacts estimates were obtained by taking a sum of global GDP divided by the sum of global population using SSP-specific estimates in 2100.

** As noted in the text, this estimate is unlikely to capture the full extent of the risks associated with continually exposing populations to extreme events such as droughts and floods, with the associated risks of mass migration and spread of disease. Such an unprecedented level of warming is well beyond the range of modern experience.

superior to existing ad hoc approaches in many IAMs. However, it also has several shortcomings. The drawback of an approach that is rooted in the empirical data, rather than in arbitrary theoretical assumptions, is that historical impacts are not necessarily a good guide to what will happen in the future. The greater the warming in the future,

24 Pretis, F., Schwarz, M., Tang, K., Haustein, K., & Allen, M. R. (2018). Uncertain impacts on economic growth when stabilizing global temperatures at 1.5 C or 2 C warming. Philo sophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 376(2119), 20160460.

25 The model estimated is a dynamic linear panel regression estimate with country and year fixed effects, linear and squared time trends and using Impulse Indicator Saturation to deal with unmodelled shifts and outliers in the data. See Appendix for further details.

26 For an extension of this approach, see Schwarz, M. & Pretis, F. (2018). Beyond Temperatures: An Economically Estimated Damage Function of 21st Century Climate Impacts using Extreme Climate Indicators. Geophysical Research Abstracts.

the further we move from historical temperatures and conditions, and therefore the less confidence we have in extrapolating the historic evidence to these higher temperatures. For instance, this empirical data-driven approach does not account for potential catastrophic tipping points and any ensuing adverse climatic effects. Also, at 4.3°C of warming, many of the human activities and living conditions we take for granted today would be seriously affected,[27,28] and a 45 per cent reduction in GDP per capita – while enormous – is unlikely to capture the full extent of the risks associated with continually exposing populations to extreme events such as droughts and floods, with the associated risks of mass migration and spread of disease. And as with all such analyses of GDP-at-risk, there is no accounting for how economic systems will respond to changing climate hazards – i.e. how much adaptation will take place. Finally, our approach does not consider the impacts that economic declines in many other countries will have on individual countries through trade, labour, and migration effects. The impacts of climate change could be even more severe than those we incorporate into our models. In short, we are more confident in the estimated damages in the 'high-ambition' and 'current policies' scenarios than the 'worst-case' scenario.

The rapid transition to a stable climate, represented by our 'high-ambition' scenario, involves the potential for stranding of assets and labour, particularly in high emitting energy generation infrastructure (Fig. 3). The expected emissions from existing and planned fossil-based infrastructure and assets (equivalent to 658 gigatons of CO_2)[29] already commits the world to exceeding 1.5°C by roughly 238 gigatons with a probability of 50 to 66 per cent. To achieve a better than 50 per cent probability of meeting the 1.5°C target, the best-case realisation of our 'high-ambition' scenario, a significant portion of the world's committed fossil assets, and any new fossil assets built subsequently, would need to be retired (stranded) before the end of their engineered lifetimes. Such estimates are based on new exhaustive research[30] and suggest that the transition cost associated with meeting the 1.5°C goal could lie

27 Arnell, N.W., Lowe, J.A., Brown, S., Lincke, D., Price, J.T., 2015, The global impacts of climate change under 1.5ºC, 2ºC, 3ºC and 4ºC pathways.

28 Fung F, Lopez A, New M (2011) Water availability in +2 degrees C and +4 degrees C worlds. Philos Trans R Soc A-Math Phys Eng Sci 369:99–116

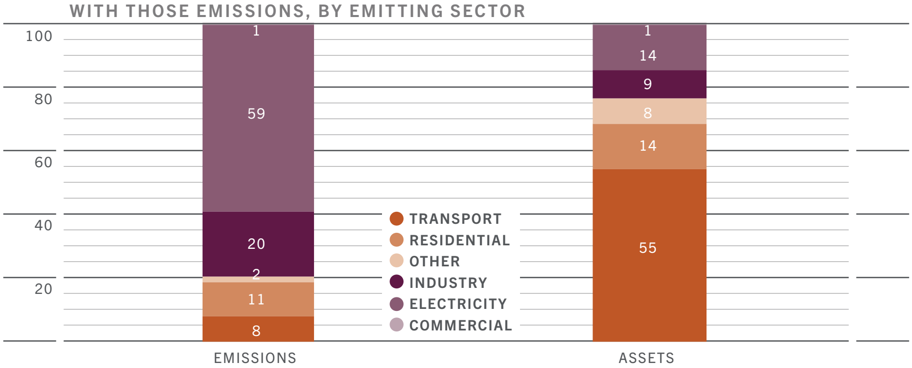
29 CO2e, or carbon dioxide equivalent, is a standard if somewhat controversial unit for combining the warming impact of different greenhouse gases. The impact of each different greenhouse gas is equilibrated in terms of the amount of CO_2 that would create the same amount of warming.

30 Tong, D. et al. 2019. Committed Emissions from Existing Energy Infrastructure Jeopardize 1.5 °C Climate Target. Nature 572(7769): 373–77. See also Pfeiffer, A., Millar, R., Hepburn, C., & Beinhocker, E. (2016). The '2 C capital stock' for electricity generation: Committed cumulative carbon emissions from the electricity generation sector and the transition to a green economy. Applied Energy, 179, 1395-1408 and Pfeiffer, A., Hepburn, C., Vogt-Schilb, A., & Caldecott, B. (2018). Committed emissions from existing and planned power plants and asset stranding required to meet the Paris Agreement. Environ mental Research Letters, 13(5), 054019.

between USD5 trillion and USD17 trillion in asset value.[31] Fig. 3 breaks down the maximum at risk asset value by key developed and emerging economies showing, that many of these assets lie in China, the EU and the US. This analysis is an important improvement on previous work[32,33] in that it calculates committed emissions from all fossil infrastructure including industrial, commercial and residential energy and domestic and international transport. A key finding is that the electricity and industrial sectors represent some 75 per cent of total committed emissions but only 25 per cent of the total asset value (Fig. 3). In other words, these are the assets that it would be most cost effective to strand first. Nearly half of these electricity and industry-sector emissions are associated with Chinese infrastructure.

FIG.3

THE PERCENTAGE OF COMMITTED EMISSIONS AND ASSET VALUES ASSOCIATED WITH THOSE EMISSIONS, BY EMITTING SECTOR



Source: Tong et al. 2019

Major cities around the globe could lose between USD300 billion and USD1 trillion in foregone economic output in any given year due to climate change-related sea-level rise. Nearly half of the cities that are most at risk are in emerging economies, including Shanghai, Guangzhou, Calcutta, Mumbai, Tianjin and Hong Kong (Fig. 5c). A key anomaly shown in Fig. 5c is that until mid-century, the global sea-level rise will be similar for all emission scenarios (darker shading), before deviating dramatically through the second half of this century (lighter shading). Most of the differences in damages between cities are a function of their respective size and exposure to a rising sea-level, but some are also due to regional differences in sea-level rises. Fig. 4 shows median regional sea level rise estimates for the three warming scenarios in 2050 and

31 This represents the theoretical range of stranded asset value estimated by the Tong et al. (2019). The maximum value results from stranding those assets with the highest asset value per committed emissions - primarily in transport. See Appendix for more details-.

32 Pfeiffer, A., Millar, R., Hepburn, C., & Beinhocker, E. (2016). The '2°C capital stock' for electricity generation: Committed cumulative carbon emissions from the electricity. generation sector and the transition to a green economy. Applied Energy, 179, 1395-1408

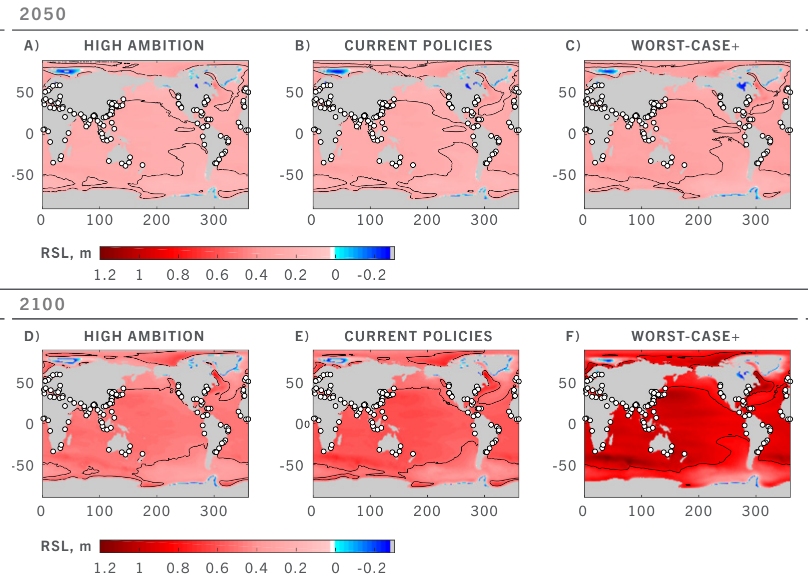
33 Pfeiffer, A., Hepburn, C., Vogt-Schilb, A., & Caldecott, B. (2018). Committed emissions from existing and planned power plants and asset stranding required to meet the Paris Agreement. Environmental Research Letters, 13(5), 054019.

2100. Cities located within river deltas also experience subsidence, some of it man-made through groundwater extraction, further increasing their exposure to sea-level rise and severe flooding (Table 8).

Among emerging market economies, China is exposed to the greatest risk, with annual average losses ranging between 3.6 and 4.7 per cent of GDP per capita on average across 15 cities by 2100. Brazil faces annual average losses ranging between 0.9 and 1.1 per cent of GDP per capita on average across 10 cities by 2100. An exceptionally vulnerable city in Brazil is Grande Vitoria, with average annual losses from sea-level rise of some 6-7 per cent of GDP per capita by 2100 (and already 2.0-3.5 per cent in 2050). Although these estimated annual costs appear large, the numbers presented are effectively equivalent to the risk associated with a single 1-in-100-year storm surge. However, it is possible that the cumulative effects of multiple smaller events over the same time horizon, when combined with the long-term sea-level rise, could result in even greater damage. Note that appropriate coastal management measures could significantly reduce the scale of this damage by up to a factor of 10, depending on the measures adopted as well as the specific circumstances of vulnerable cities.[34]

FIG.4

MEDIAN RELATIVE SEA-LEVEL PROJECTIONS IN 2050 AND 2100 FOR THREE WARMING SCENARIOS. BLACK CONTOUR REPRESENTS GLOBAL SEA LEVEL IN EACH PANEL: A) 0.21, B) 0.23, C) 0.28, D) 0.44, E) 0.53, AND F) 0.85 M.*



Source: Projections from Jackson and Jevrejeva (2016) and Jackson et al. (2018).

* Location of cities assessed are marked by black circles. Worst Case+ refers to the High-end scenario of Jackson & Jevrejeva (2016), which follows our 'worst-case' scenario but uses a larger contribution to global sea level from the ice sheets.

34 Jevrejeva, S., Jackson, L.P., Grinsted, A., Lincke, D. and Marzeion, B., 2018. Flood damage costs under the sea-level rise with warming of 1.5°C and 2°C. Environmental Research Letters, 13(7), p.074014.

Impacts on ecosystems will threaten enormous tracts of life on the planet. Not achieving the Paris Agreement will, it is estimated, result in a biodiversity loss equivalent to up to 8 million square kilometres of pristine habitat – a land mass the size of Australia. This finding is based on a recent analysis of biodiversity changes under climate change.[35] The research suggests that all three warming scenarios will result in an overall biodiversity loss, measured as a decrease in mean species abundance (MSA) (Fig. 5d). The estimated loss of biodiversity in the 'high-ambition' scenario (coupled with the sustainability socioeconomic pathway) would result in roughly 2.5 million square kilometres of pristine habitat around the world being converted to land where all the original species are no longer present by 2050.[36]

The decline under the 'current policies' warming scenario coupled with the 'regional rivalry' socioeconomic pathway is very similar to the 'worst-case' warming with 'fossil-fuelled development' pathway, and roughly equivalent to 8m km^2 of pristine habitat lost by 2050 compared to 2015.[37] These latter two scenario and pathway combinations are similar as they both represent combinations of low mitigation and environmental sustainability efforts. The largest declines are to be found in Africa while the smallest declines are around China and North America (Fig. 5d).

All such analyses are heavily reliant on the simplifying assumptions made. Those made for this study are summarised in Table 2.

35 Schipper, Aafke M. et al. 2020. Projecting Terrestrial Biodiversity Intactness with GLOBIO 4. Global Change Biology 26(2): 760–71.

36 The estimated global area weighted average MSA values under the 'high-ambition' scenario coupled with the sustainability socioeconomic pathway (RCP2.6+ SSP1) decline by 0.02.

37 The MSA values decline is 0.06 in the 'current policies' warming scenario coupled with 'regional rivalry' socioeconomic pathway (RCP6.0+SSP3), and 0.05 in the 'worst-case' warming with 'fossil-fuelled development' pathway (RCP8.5+SSP5).

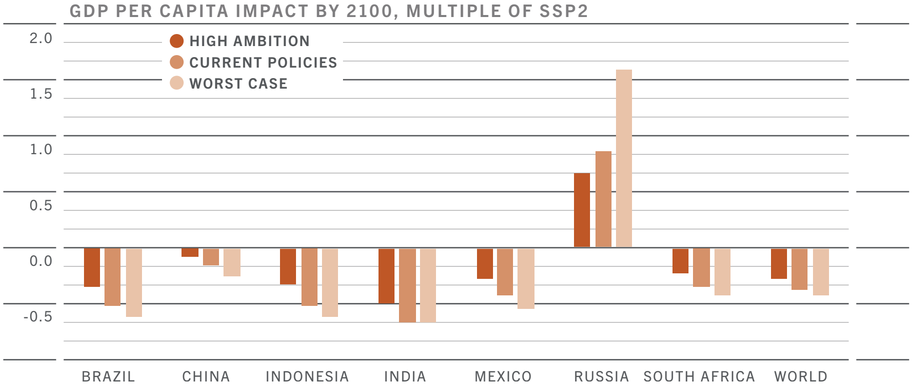
FIG.5

SUMMARY PANEL OF CLIMATE RISKS

FIG.5A

Estimated economic impact (GDP per capita) of climate change in 2100 for the world and key emerging economies in each of the three warming scenarios

GDP PER CAPITA IMPACT BY 2100, MULTIPLE OF SSP2



* Results based on historical economic-metric estimates and projected using CMIP5 Climate Models. Results show the mean difference to a Baseline Scenario (SSP) without climate impacts

FIG.5B

The theoretical maximum asset value exposed to transition risk from a 66 per cent chance of meeting the 1.5 degrees for key countries

MAXIMUM ASSET VALUE EXPOSED TO TRANSITION RISK IN THE HIGH AMBITION SCENARIO, USD TRN

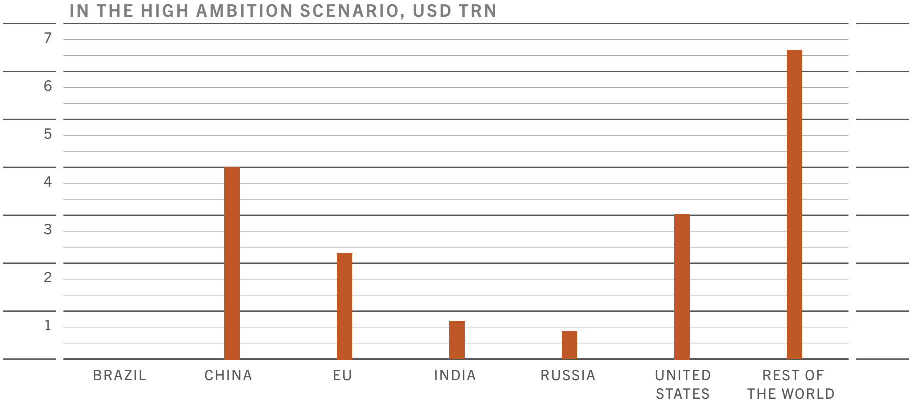


FIG.5C

Annual average losses from a 1-in-100-year storm surge by 2100 for major emerging-economy cities under the 3 different scenarios

SEA-LEVEL DAMAGE, AVERAGE ANNUAL LOSSES AS SHARE OF GDP, %

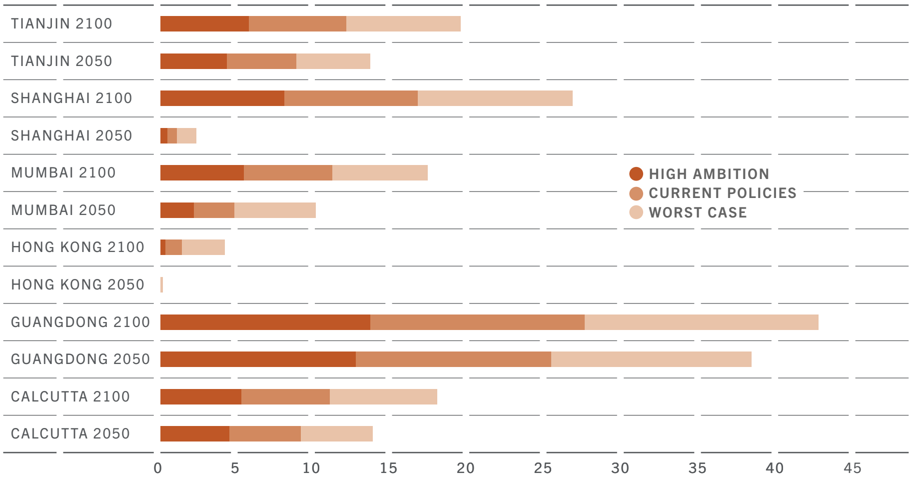


FIG.5D

Biodiversity loss, as measured by a reduction in Mean Species Abundance, for the world and major economies under the three different scenarios

IMPACTS ON BIODIVERSITY, CHANGE IN MEAN SPECIES ABUNDANCE
CHANGE IN MEAN SPECIES ABUNDANCE (MSA0)

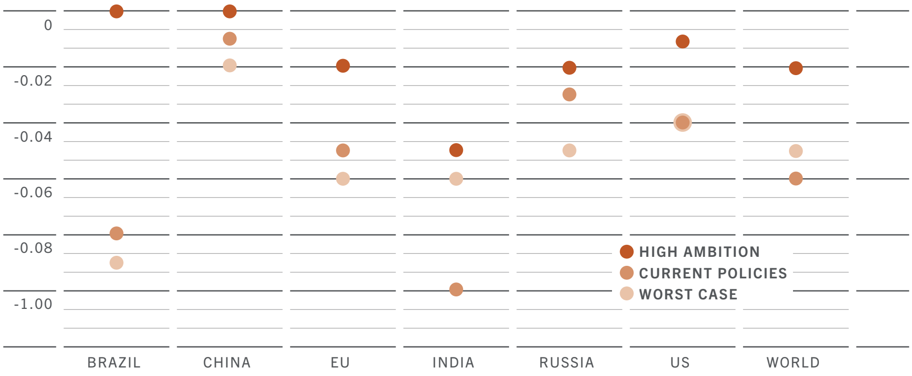
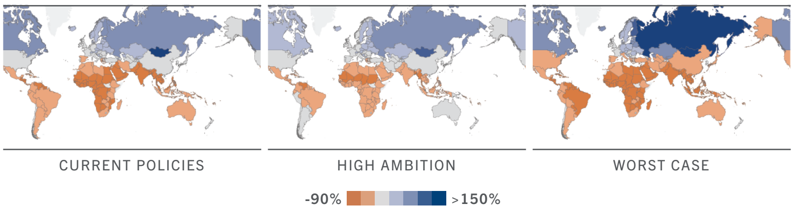


FIG.5E

Estimated economic impact (GDP per capita) of climate change in 2100 (compared to the economic growth estimates associated with the SSP2 socioeconomic pathway)

GDP PER CAPITA IMPACTS BY COUNTRY BY 2100 BY SCENARIO,
% CHANGE RELATIVE TO SSP2



Sources: a) this report b) Ton ; et al. 2019, c) this report, d) Schi ›per et al. 2020 e) this report

TABLE 2

SUMMARY OF THE METHODOLOGIES AND ASSUMPTIONS USED FOR THE ESTIMATION OF THE GDP PER CAPITA IMPACTS OF CLIMATE CHANGE

ESTIMATION	METHOD	ASSUMPTIONS
GLOBAL TEMPERATURE ANOMALY	Choice of emission pathways derived from the Integrated Assessment Models used in the IPCC Special Report on Global Warming of 1.5°C. We chose two emission pathways based on their median warming by 2100 as well as the 'worst-case' baseline (RCP8.5). The 'current policies' scenario was chosen based on current levels of ambition, as estimated by the Carbon Tracker Project, which result in roughly 3°C of warming by the end of the century.	We assume that the simple climate models used here are consistent emulators for global temperature dynamics. This is well supported in the literature.
REGIONAL CLIMATE CHANGE	Based on the identification of the Global Mean Temperature Anomaly using simple climate models (above), identification of suitable CMIP5 General Circulation Model to represent regional climate change. We do this by matching end-of-century global mean temperature anomalies to the simple climate model outputs. CMIP5 data was subsequently post-process resampled and aggregated to allow suitable estimation.	We assume that the estimated global mean temperature anomaly in GCMs and SCMs is consistent and then further that GCMs are an adequate representation of future climate systems.
GDP PER CAPITA IMPACT	Empirical estimation based on data between 1962 and 2017. Carried out using a dynamic panel regression model with linear and non-linear country-specific time trends and country- and time-fixed effects, controlling for outliers using Impulse Indicator Saturation. In the estimation, we exploit year-to-year variation in temperature and economic growth. For details see Pretis et al. 2018. A narrative is provided, explaining the likely direction of bias in the results due to missing international trade feedback dynamics in the individual country analyses.	We assume that the historical relationship, as estimated, holds into the future. This means that we assume that a year-to-year temperature impact in the future is the same as we have observed in the past – even if its magnitude is larger. Base-level growth, upon which the climate effect is added, is taken from the Shared Socioeconomic pathways. We estimated the impact of climate shocks on economic development in the past and then used this relationship to estimate how large such an impact could be under different climate and social scenarios.
BIODIVERSITY IMPACT	The estimated changes in biodiversity are based on an application of the GLOBIO4 model, which approximates the impact of climate change on Mean Species Abundance (MSA) and pristine habitat loss equivalence, based on Schipper et al. 2020.	Applying this approach requires us to assume that the SSPs employed for the RCP scenarios that match our warming scenarios are the most likely SSPs to result in these RCPs. Similar assumptions have been employed in another IPCC-based research.
SEA-LEVEL IMPACT	Extension of the modelling approach suggested by Hallegatte et al. (2013) using newly developed regional sea-level projections for RCP 2.6, 4.5/6.0 and 8.5 from Jackson & Jevrejeva (2016) and Jackson et al. (2018)	We assume that present-day protection heights are maintained and overtopping of defences by a storm surge results in complete inundation of elevations up to that water level.
TRANSITION RISK	Employing the range of potential assets at risk developed by Tong et al. (2019).	Value based on an extensive database of existing and proposed assets, their values, expected lifetimes, expected capacity factors and emissions.
CURRENT SHARE OF COMMITTED EMISSIONS AND ASSET VALUE	Employing the range of potential assets by sector stranding developed by Tong et al. (2019).	A range is used as the RCPs involve a temperature range; asset stranding depends heavily on the order and aggressiveness of mitigation policies in various sectors. For instance, an aggressive policy to replace petrol and diesel vehicles with electric vehicles in the next decade (before the electricity grid is decarbonised) would result in a much higher asset cost and much higher emissions.

1.2 Regional impacts

Without climate action by both developed and developing economies, GDP per capita in countries in the tropics and sub-tropics, such as Brazil, India and Indonesia, could be up to 59 per cent lower than the baseline by 2100. Figs 4a and 4e show, respectively, the reduction in GDP per capita in 2100 compared to baseline for key emerging countries and the rest of the world in each of the three warming scenarios. GDP per capita is seen to decline for most emerging economies such as Brazil, India, China, Indonesia and Mexico. GDP per capita is also set to decline in developed countries such as the US, Japan and Australia. However, countries in higher-latitude, such as Russia and parts of the EU27, could see a rise in GDP per capita relative to the baseline estimate (SSP2). Note that these impacts should be interpreted as applying to economies in isolation (i.e. assuming that the higher latitude countries are not dragged down by the economic declines in the rest of the world).[38] The magnitude of such impacts should therefore be considered with caution, as uncertainties remain high and precision low. Nevertheless, the overall economic effect of climate change is consistent and remains the same after performing sensitiveness analyses.[39]

We then narrow our focus from this general outlook to review the latest evidence on the impact climate change has on specific emerging economies, starting with the two largest, China and India, followed by Brazil, Indonesia, Mexico, Russia and South Africa. A growing volume of literature highlights how extreme temperature and precipitation can lead to conflict,[40] lower productivity,[41] increase mortality and morbidity,[42] and cause sectoral and geographical reallocations.[43] While natural disasters are particularly salient instances of climatic extremes, it is worth noting that even warm days (those with a minimum tem-

38 Especially, the estimated increase in GDP per capita for Russia does not account for the impact that economic declines in the rest of the world might have on the Russian economy and demand for Russian goods.

39 More specifically, the sign of the country-specific impact estimates is robust to the specification of the underlying econometric model, i.e. does not change when we choose to use a modified estimation procedure. The sign is also robust to the choice of the estimation period used, whether Impulse Indicator Saturation is used or not, as well as to the inclusion of precipitation. This result is consistent with a wide range of models used in the existing literature, e.g. see Burke et al. (2015) and Pretis et al. (2018).

40 Hsiang, S. M., Burke, M., & Miguel, E. (2013). Quantifying the influence of climate on human conflict. Science, 341(6151), 1235367.

41 Burke, M., Hsiang, S. M., & Miguel, E. (2015). Global non-linear effect of temperature on economic production. Nature, 527(7577), 235-239.

42 Burgess, R., Deschenes, O., Donaldson, D., & Greenstone, M. (2011). Weather and Death in India: Mechanisms and Implications for climate change. Cambridge, United States: Massachusetts Institute of Technology. Mimeographed document.

43 Colmer, J. (2018). Weather, labor reallocation and industrial production: evidence from India. Mimeographed document.

perature of 25°C) can be harmful, lowering life expectancy, causing crime rates to rise and depressing worker productivity. These impacts are often greater in low- and middle-income countries, which do not tend to have the infrastructure in place to cope with weather extremes.

Stringent climate action could prevent these negative effects. Governments are in a unique position to use the Covid-19 stimulus packages to tackle climate change as well as reboot the economy.

1.2.1 China

China could be among the countries most severely affected by climate change.[44] Experiencing a 0.9-1.5°C average rise in temperature in the last century, China's warming has been faster than the global average.[45] On 24 July 2015, the country recorded its highest ever temperature of 50.3°C, in Xinjiang province.[46] Temperature records have since been broken in several regions, with 24 new ones set in 2018 alone.[47] Global warming is also dramatically changing rainfall patterns, with a 10 per cent increase in 'heavy rain' days and a 13 per cent decrease in 'light rain' days in 2016 relative to 1961.[48]

Flooding is expected to put infrastructure and livelihoods at high risk, especially in the cities of Beijing, Tianjin, Jiangsu, Shanghai and Zhejiang. In July 2012, Beijing suffered its heaviest rainfall in 60 years.[49] Currently, 103 million people in China rely on transport infrastructure that is vulnerable to flooding risk.[50] Climate-related river flooding could cost China USD175 billion between 2016 and 2035.[51] In parallel, sea levels off the coast of eastern China have been rising at a speed of 2.9 mm per year from 1980 to 2012, a higher pace than the global average.[52] By the end of the century, the median coastal sea level could rise by 48-61 cm (the forecast we use for our 'current policies' emissions scenario).[53] With a population of more than 550 million, China's coastal provinces are among the most densely populated regions in the world. Many megacities located in low-lying areas, including Shanghai, Tianjin,

44 China's Intended Nationally Determined Contributions (2015).
45 Wang, B., Hong, G., Cui, C. Q., Yu, H., & Murty, T. (2019). Comprehensive analysis on China's National Climate Change Assessment Reports: Action and emphasis. Frontiers of Engineering Management, 6(1), 52-61.
46 David Sandalow (2019). Guide to Chinesea Climate Policy 2019.
47 Ibid.
48 China Meteorological Administration (17 February 2017), Global warming has changed pattern of warming in China, available at: http://www.cma.gov.cn/en2014/news/News/201702/t20170217_393070.html
49 BBC (2012). Beijing chaos after record floods in Chinese capital, available at: https://www.bbc.co.uk/news/world-asia-china-18942984
50 Hu, X., Hall, J. W., Shi, P., & Lim, W. H. (2016). The spatial exposure of the Chinese infrastructure system to flooding and drought hazards. Natural Hazards, 80(2), 1083-1118.
51 Willner, S. N., Otto, C., & Levermann, A. (2018). Global economic response to river floods. Nature Climate Change, 8(7), 594-598.
52 Wang, B., Hong, G., Cui, C. Q., Yu, H., & Murty, T. (2019). Comprehensive analysis on China's National Climate Change Assessment Reports: Action and emphasis. Frontiers of Engineering Management, 6(1), 52-61.
53 Qu, Y., Jevrejeva, S., Jackson, L. P., & Moore, J. C. (2019). Coastal Sea-level rise around the China Seas. Global and planetary change, 172, 454-463.

Shenzhen and Guangzhou are vulnerable to ocean flooding and will increasingly depend on coastal defences. For example, there is a 50 per cent probability that a large part of Shanghai will be below sea level in 2100 because of climate change ('current policies' scenario).[54]

Manufacturing and industrial activities could also be heavily affected by climate change. One study predicts that by 2050 climate change could reduce Chinese manufacturing output by 12 per cent in the absence of adaptation.[55] Labour-intensive industries could face sharp reductions in productivity if temperatures become unbearable for workers. Climate change also puts energy supply and water security at risk. The Chinese government's Third National Assessment Report warns that climate change might impact the safety and stability of China's key infrastructures, such as the Three Gorges Dam, Qinghai-Tibet Railway and the South-North Water Transfer Project.[56] Droughts could directly affect 6 million electricity users if, as is likely, the hydroelectric and thermoelectric power plants they rely on suffer from water shortages.[57]

Climate change may lead to a 13 per cent decrease in Chinese crop yields by 2050 compared to 1996-2000,[58] though, depending on land conditions and crop types, impacts could vary. Our modelling suggests that the impact of climate change on Chinese agriculture will lead to an overall decline in Chinese GDP per capita of 2 per cent in the 'worst-case' warming scenario (compared to baseline). This is the result of two opposing effects. On the one hand, warming lengthens the crop-growing season, making earlier planting and later harvesting possible, and expands the arable land for some crops. For example, cotton in north-west China saw a nine-day lengthening of its growing season over the period 1983 to 2004,[59] and rice planting has been expanded in Heilongjiang province from 0.22 mega hectares (Mha) in the early 1980s to 2.25 Mha in 2007.[60] In general, rising temperatures at night have increased rice yields in the north-east part of China by 4.5-14.6 per cent

54 Climate Central (2019). Flooded future: Global vulnerability to sea-level rise worse than previously understood. (Available at: https://www.climatecentral.org/pdfs/2019CoastalDEMReport.pdf)
55 Zhang, P., Deschenes, O., Meng, K., & Zhang, J. (2018). Temperature effects on productivity and factor reallocation: Evidence from half a million Chinese manufacturing plants. Journal of Environmental Economics and Management, 88, 1-17.
56 Wang, B., Hong, G., Cui, C. Q., Yu, H., & Murty, T. (2019). Comprehensive analysis on China's National Climate Change Assessment Reports: Action and emphasis. Frontiers of Engineering Management, 6(1), 52-61.
57 Hu, X., Hall, J. W., Shi, P., & Lim, W. H. (2016). The spatial exposure of the Chinese infrastructure system to flooding and drought hazards. Natural Hazards, 80(2), 1083-1118.
58 Piao, S., Ciais, P., Huang, Y., Shen, Z., Peng, S., Li, J., ... & Friedlingstein, P. (2010). The impacts of climate change on water resources and agriculture in China. Nature, 467(7311), 43-51.
59 Wang, H. L., Gan, Y. T., Wang, R. Y., Niu, J. Y., Zhao, H., Yang, Q. G., & Li, G. C. (2008). Phenological trends in winter wheat and spring cotton in response to climate changes in north-west China. Agricultural and Forest Meteorology, 148(8-9), 1242-1251.
60 You, L., Rosegrant, M. W., Wood, S., & Sun, D. (2009). Impact of growing-season temperature on wheat productivity in China. Agricultural and Forest Meteorology, 149(6-7), 1009-1014.

per degree Celsius. On the other hand, there was a 4.5 per cent decrease in wheat yields due to higher temperatures between 1979 and 2000.[61] Higher temperatures also caused problems with pests and disease. The area of agricultural land affected by pest and disease increased from approximately 100 Mha in the 1970s to 345 Mha in the mid-2000s. Additionally, rising temperatures can lead to droughts that are detrimental to rainfed farms.[62] Droughts and flood exacerbated by climate change caused a harvest failure equivalent to a sown area of 5Mha per year between 2000 and 2007.[63] North-eastern China suffered a 37 per cent increase in drought days in 2016 compared to historical averages.

China is also particularly susceptible to transition risk if ambitious climate goals are to be achieved and action is delayed. This is because almost half of the world's electricity and industrial assets – infrastructure that is most at risk from stranding – are in China.[64]

1.2.2 India

Climate changes poses a serious threat to Indian agriculture. Research shows that a further 1°C increase in annual mean temperature would result in a 12.7 per cent reduction in agricultural yield in the average district and a 12.6 per cent reduction in the value of production.[65] Our modelling suggests an overall decline in GDP per capita for Indian agriculture of 7 per cent in the 'worst-case' scenario. About 56 per cent of India's agriculture by area is rain-fed, making it particularly sensitive to changes in weather conditions.[66] In the most severe climate scenarios, it is possible that the monsoon weather system may even collapse (even though monsoons are notoriously difficult to model correctly).[67] Since around 70 per cent of rural Indian households depend on agriculture for their livelihoods, the ramifications of climate change on the country's development are likely to be significant.[68]

61 Tao, F., Yokozawa, M., Liu, J., & Zhang, Z. (2008). Climate–crop yield relationships at provincial scales in China and the impacts of recent climate trends. Climate Research, 38(1), 83-94.
62 Wang, J., Mendelsohn, R., Dinar, A., Huang, J., Rozelle, S., & Zhang, L. (2009). The impact of climate change on China's agriculture. Agricultural Economics, 40(3), 323-337.
63 Piao, S., Ciais, P., Huang, Y., Shen, Z., Peng, S., Li, J., ... & Friedlingstein, P. (2010). The impacts of climate change on water resources and agriculture in China. Nature, 467(7311), 43-51.
64 Tong, D. et al. 2019. Committed Emissions from Existing Energy Infrastructure Jeopardize 1.5 °C Climate Target. Nature 572(7769): 373–77.
65 Colmer, J. (2018). Weather, labor reallocation and industrial production: evidence from India.
66 Suresh, A., Raju, S. S., Chauhan, S., & Chaudhary, K. R. (2014). Rainfed agriculture in India: An analysis of performance and implications. Indian Journal of Agricultural Sciences, 84(11), 1415-22.
67 Turner, A., Annamalai, H. (2012). Climate change and the South Asian summer monsoon. Nature Climate Change 2, 587–595 https://doi.org/10.1038/nclimate1495
68 Government of India, Ministry of Finance, 2020. India Economic Survey 2019-2020.

Productivity in other sectors will also be negatively affected. Research shows that ambient temperatures have non-linear effects on worker productivity across all sectors of the economy, with declines of 4 to 9 per cent for every one degree rise in temperature on hot days.[69] India's manufacturing sector is labour-intensive and many manufacturing units do not have any form of climate control (e.g. air conditioning). This means that workers are vulnerable to high temperatures. Evidence suggests that a one degree increase in temperature causes a 9 per cent drop in manufacturing productivity and 7 per cent decrease in average wages. The employment of casual workers falls by 12 per cent and the number of items produced decreases by 6 per cent.[70] Firms that keep their employees cool do not suffer these impacts.

The knock-on effects of high temperatures will also affect education and therefore long-term human capital accumulation and economic development. It has been found that high temperatures reduce maths and reading test scores,[71] including among school-age children in India.[72] It is posited that agricultural income influences this relationship. Hot days during the growing season reduce agricultural yields, which in turn affect the livelihoods and therefore performance of school pupils. By contrast, the effect of hot days in the non-growing season is comparatively modest. The roll-out of welfare programmes that provide safety nets for the poor "substantially weaken the link between temperature and test scores".[73]

Climate change could also have wider structural impacts on the economy. Rising incomes allow farmers and their families to migrate to cities to seek education and jobs in manufacturing and services. A fall in those incomes would make it harder for such groups to pursue opportunities beyond subsistence agriculture. There is "evidence that rising temperatures [in India] are associated with lower rates of urbanisation, higher shares of workers in agriculture, and lower shares of workers in non-agriculture."[74] These effects are concentrated in districts with sparse road infrastructure, which suggests that higher temperatures exacerbate the economic constraints faced by rural, isolated households, and subsequently limit rural-urban

69 Somanathan, E., Somanathan, R., Sudarshan, A., & Tewari, M. (2015). The impact of temperature on productivity and labor supply: Evidence from Indian manufacturing. Indian Statistical Institute: New Delhi, India.
70 Colmer, J. (2018). Weather, labor reallocation and industrial production: evidence from India. Mimeo.
71 Park, R. Jisung, et al. Heat and learning. American Economic Journal: Economic Policy 12.2 (2020): 306-39.
72 Garg, T., Jagnani, M., & Taraz, V. (2018). Temperature and human capital in India. Available at SSRN 2941049.
73 Ibid.
74 Maggie Y. Liu, Yogita Shamdasani, and Vis Taraz. February (2020). Climate change, structural transformation, and infrastructure: Evidence from India. Pre-print.

and sectoral mobility.[75] Climate change is essentially inhibiting typical economic development patterns, which see movement away from the farm and towards manufacturing and services.

The human costs of climate change are also significant. A single day above 35°C elevates annual mortality by 0.74 per cent in India, relative to a day between 21 and 23°C (for comparison, an equivalent increase in temperature in the US increases mortality by only 0.03 per cent).[76] This is because the Indian population – particularly the rural poor – is more exposed to temperature extremes. Moreover, an increase in the frequency of hot days by a third elevates annual mortality among rural populations by 7.3 per cent.[77] While there are many explanations for why this is the case, the indirect impact of lost agricultural income appears to be an obvious one. Farmers who see their yields drop are also left in a desperate situation, with little insurance to fall back on and debts to pay off. For temperatures above 20°C, a one degree increase in temperature has been linked to around 70 more suicides on average,[78] amounting to nearly 60,000 suicides over the past 30 years in India.[79]

The relationship between weather and conflict/political stability in India is also now being investigated. The theory is that when resources become scarce, in-fighting between communities over resources increases. To this end, research has found that that negative rainfall shocks increase Muslim-Hindu riots in Indian states.[80]

Overall, climate change is already influencing India's growth and development and will continue to do so. On top of the effects of temperature increases that are reported in most of the available studies on the impacts of climate change in India, there are other low-probability, high-cost risks, including the collapse of the monsoon weather system, which will have catastrophic consequences. India already suffers from extreme weather events and loses billions of dollars to floods every year. Tackling climate change as well as investing in adaptation will be needed to safeguard India's ongoing economic growth and development.

75 Ibid.
76 Burgess, R., Deschenes, O., Donaldson, D., & Greenstone, M. (2011). Weather and Death in India: Mechanisms and Implications for climate change. Cambridge, United States: Massachusetts Institute of Technology. Mimeographed document.
77 Ibid.
78 Carleton, T. A. (2017). Crop-damaging temperatures increase suicide rates in India. Proceedings of the National Academy of Sciences, 114(33), 8746-8751.
79 Ibid.
80 Bohlken, A. T., & Sergenti, E. J. (2010). Economic growth and ethnic violence: An empirical investigation of Hindu—Muslim riots in India. Journal of Peace Research, 47(5), 589-600.

1.2.3. Brazil

Climate change is expected to have strong impacts on water availability in Brazil. Brazil is expected to become drier as the climate changes.[81, 82] By the end of the 21st century, 67 per cent of the country is likely to be classified as arid. By then, areas in the north and north-east will have reached dryness levels typical of deserts. In the driest regions of Brazil, the rivers Tocantins, Paraná and São Francisco could see their flows reduced by up to 70 per cent by 2100 as dry seasons grow longer. In the Amazon region, the rivers Araguaia, Tocantins and Xingu will be the most affected.[83] The Amazon forest is the most vulnerable biome in Brazil. Studies indicate that the Amazon influences the rain regimes in other Brazilian regions[84,85] and that climate change could lead to strong disruptions in rainfall patterns.

Under business-as-usual climate scenarios, agricultural harvests will be exposed to frequent droughts. Our modelling suggests the impact of drought on national agriculture could equate to a 5 per cent decline in the sector's contribution to total Brazilian GDP per capita in the 'worst-case' warming scenario. The effect of climate change on Brazilian agriculture will vary by region and the type of crop. For example, bean production, which largely takes place in the south of the country, may shrink by 57 per cent. Meanwhile, Brazil's corn harvest in January-April (called *safrinha*) may no longer be possible, and areas suitable for corn cultivation may decline by up to 90 per cent during the rest of the year. Adequate areas for soy production may contract by up to 81 per cent, and such activity may end up being concentrated in the Amazon's southern fringes, putting further pressure on its forests.[86] Rice production could also be affected. Brazil could experience a 13 per cent loss in the amount of land suitable for rice growing. Production could become confined to irrigable areas in the Brazilian western-central region. Cotton pro-

81 de Queiroz, A.R., Faria, V.A.D., Lima, L.M.M. and Lima, J.W.M., 2019. Hydropower revenues under the threat of climate change in Brazil. Renewable Energy, 133, pp. 873-882.

82 Borges de Amorim, P., & Chaffe, P. B. (2019). Towards a comprehensive characterization of evidence in synthesis assessments: the climate change impacts on the Brazilian water resources. Climatic Change, 155(1), 37-57.

83 Ministério da Ciência, Tecnologia e Inovação. Secretaria de Políticas e Programas de Pesquisa e Desenvolvimento. Coordenação-Geral de Mudanças Globais de Clima. Modelagem climática e vulnerabilidades Setoriais à mudança do clima no Brasil / Ministério da Ciência, Tecnologia e Inovação. Brasília: Ministério da Ciência, Tecnologia e Inovação, 2016.

84 Gomes, N. M. O. Transporte de vapor d'água da amazônia para o centro oeste, sul e sudeste do Brasil a partir de dados de reanálise. 2019. 51 f. Dissertação (Mestrado em Meteorologia) – Pós-Graduação em Meteorologia, Centro de Tecnologia e Recursos Naturais, Universidade Federal de Campina Grande, Paraíba, Brasil, 2019.

85 Amorim, Tamiris Xavier, Mônica Carneiro Alves Senna, and Marcio Cataldi. "Impactos do desmatamento progressivo da Amazônia na precipitação do Brasil." Revista Brasileira de Climatologia 24 (2019).

86 Borges de Amorim, P., & Chaffe, P. B. (a2019). Towards a comprehensive characterization of evidence in synthesis assessments: the climate change impacts on the Brazilian water resources. Climatic Change, 155(1), 37-57.

duction will also be hit. In some regions, areas suitable for cotton production will reduce in size by a modest 1.5 per cent. But other regions could face severe reductions. In the state of Bahia, currently the second largest cotton producer in Brazil, low-risk areas suitable for cotton growing, defined as areas in which farmers can expect climatic conditions for production to remain optimal, may decline by 75 per cent by 2040.[87] If new cotton varieties that can tolerate high temperatures and droughts are not developed, a drop in production could impact the whole Brazilian economy. Food insecurity, inflation, disruption to land market and population displacement are among possible consequences, aggravating living and health conditions, particularly for the poor.

One of the major industry sectors in Brazil to be affected by climate change is energy. A large share of Brazilian primary energy production comes from sugarcane (16.6 per cent) and hydropower (11 per cent of primary energy production, amounting to 60 per cent of Brazil electricity supply).[88] While studies have found that sugarcane productivity should not be heavily affected by warmer temperatures in Brazil,[89] sugarcane production could start competing for water resources with other crops as seasons become dryer.[90] At the same time, there is little doubt that climate change will have a severe impact on hydropower plants in the Amazon,[91] even though the exact nature of those effects is uncertain. Some studies show a risk of 15 per cent generation reduction in existing hydropower plants from 2041, and a 25 per cent reduction on the capacity of future ones.[92] Such projections point to significant revenue losses for all dams in the Amazon region, with generation capacity falling to zero by the end of the 21st century under some scenarios.

Flash flooding and landslides are also expected to affect critical infrastructure. These natural disasters are already major causes of disruption in the country. Currently, 58 per cent of Brazilian municipalities are prone to floods or torrents during the wet season. This ratio will increase,

87 Assad, E. D., Martins, S. C., Beltrão, Napoleão Esberard de Macêdo, & Pinto, H. S. (2013). Impacts of climate change on the agricultural zoning of climate risk for cotton cultivation in Brazil. Pesquisa Agropecuária Brasileira, 48(1), 1-8.

88 Empresa de Pesquisa Energética - EPE (2019). Balanço Energético Nacional 2019: Ano base 2018. Brazilian Energy Balance 2019 Year 2018. Empresa de Pesquisa Energética - EPE - Rio de Janeiro.

89 Evangelisa, Marin, Zullo Junior (2009). Impacto das mudanças climáticas sobre a produção de cana-de-açúcar no estado de Goiás. EMBRAPA - Empresa Brasileira de Pesquisa Agropecuária.

90 Furtado, A. T., Zullo Junior, J., & Pfeiffer, C. C. (2016). Planejamento da produção de cana-de-açúcar no contexto das mudanças climáticas globais (DGO - Digital original ed.) Editora da Unicamp.10.7476/9788526814998.

91 Mendes, C. A. B., Beluco, A., & Canales, F. A. (2017). Some important uncertainties related to climate change in projections for the Brazilian hydropower expansion in the Amazon. Energy, 141, 123-138. 10.1016/j.energy.2017.09.071.

92 Empresa de Planejamento Energético (n.d.). Análise Socioambiental. Retrieved February 24, 2020, from http://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-423/topico-489/10%20An%C3%A1lise%20Socioambiental.pdf

particularly in the south, as climate change gathers pace. The mountains and the hilly coasts by the sea in south-eastern and southern Brazil are expected to see landslides occur more frequently, with particularly dire consequences for the poor who inhabit unauthorised development areas in the hills surrounding coastal areas.[93] Droughts will also become more frequent as temperatures increase. Even at current temperatures almost 49 per cent of Brazilian municipalities are affected by drought during the dry season. In some north-eastern areas, the rate is much higher. In the north-eastern state of Ceará, 98 per cent of municipalities were affected by drought in 2017, while some regions experienced a full year of drought in 2018.[94, 95]

Furthermore, extreme heat in Brazil's northern states could constitute a major public health hazard. By 2030, the estimated annual loss in work hours due to extreme heat in Brazil could amount to around 850,000 full-time positions, compared to 314,000 in the 1990s.[96] Average temperatures in northern states are expected to push the mortality rate up by 1.7 per cent at the end of the 21st century in the most optimistic scenario, and by 8.2 per cent in most pessimistic one.[97] Some diseases may also spread more readily due to higher temperatures. Faecal-oral transmission diseases, such as diarrhoea or poliomyelitis, and rodent-borne illnesses, such as leptospirosis or hantavirus, are likely to become more prevalent in municipalities prone to flooding.[98, 99]

93 Brasil. Ministério da Ciência, Tecnologia e Inovação. Secretaria de Políticas e Programas de Pesquisa e Desenvolvimento. Coordenação-Geral de Mudanças Globais de Clima. Modelagem climática e vulnerabilidades Setoriais à mudança do clima no Brasil / Ministério da Ciência, Tecnologia e Inovação. Brasília: Ministério da Ciência, Tecnologia e Inovação, 2016.

94 Instituto Brasileiro de Geografia e Estatística – IBGE (2019, May 03). Desastres Naturais: 59,4% dos municipios não têm plano de gestão de riscos. Retrieved March 01, 2020, from https://agenciadenoticias.ibge.gov.br/agencia-noticias/2012-agencia-de-noticias/noticias/21633-desastres-naturais-59-4-dos-municipios-nao-tem-plano-de-gestao-de-riscos

95 Watts, N., Amann, M., Arnell, N., Ayeb-Karlsson, S., Belesova, K., Boykoff, M., Byass, P., Cai, W., Campbell-Lendrum, D., Capstick, S., Chambers, J., Dalin, C., Daly, M., Dasandi, N., Davies, M., Drummond, P., Dubrow, R., Ebi, K. L., Eckelman, M., . . . Montgomery, H. (2019). The 2019 report of The Lancet Countdown on health and climate change: ensuring that the health of a child born today is not defined by a changing climate. The Lancet, 394(10211), 1836-1878. 10.1016/S0140-6736(19)32596-6.

96 International Labour Office - ILO (2019). Working on a warmer planet: The impact of heat stress on labour productivity and decent work. Geneva, International Labour Office.

97 Gasparrini, A., Guo, Y., Sera, F., Vicedo-Cabrera, A. M., Huber, V., Tong, S., de Sousa Zanotti Stagliorio Coelho, Micheline, Nascimento Saldiva, P. H., Lavigne, E., Matus Correa, P., Valdes Ortega, N., Kan, H., Osorio, S., Kyselý, J., Urban, A., Jaakkola, J. J. K., Ryti, N. R. I., Pascal, M., Goodman, P. G., . . . Armstrong, B. (2017). Projections of temperature-related excess mortality under climate change scenarios. The Lancet Planetary Health, 1(9), e360-e367. 10.1016/S2542-5196(17)30156-0.

98 Ahern, M., Kovats, R. S., Wilkinson, P., Few, R., & Matthies, F. (2005). Global Health Impacts of Floods: Epidemiologic Evidence. Epidemiologic Reviews, 27(1), 36-46. 10.1093/epirev/mxi004.

99 Wu, X., Lu, Y., Zhou, S., Chen, L., & Xu, B. (2016). Impact of climate change on human infectious diseases: Empirical evidence and human adaptation. Environment International, 86, 14-23.

1.2.4. Indonesia

Indonesia is the world's largest archipelago, and with most of its population living along coastlines, it is particularly vulnerable to climatic changes. Flooding and coastal inundation are perennial challenges, which are only getting worse as climate change advances. The main risk is to the island of Java, which accounts for two-thirds of Indonesia's population and over half of the country's poor. The population's lack of adaptive capacity is of particular concern.[100]

Indonesia is also heavily dependent on natural resources. The country's water availability, agriculture, fisheries and forests are all susceptible to climate change. Water shortages, for example, are becoming more acute in the dry season. In response, industries are boring ever deeper underground to tap into the groundwater table. The consequence is a higher vulnerability to land subsidence and salt-water intrusion.[101]

Indonesia's agricultural sector, which contributes 12.8 per cent to its GDP[102] and employs 30 per cent of the labour force[103], is extremely vulnerable to climate change. Rice is a staple crop in Indonesia, where production falls with rises in temperature. Research shows that climate change could trigger rice shortages, threatening food security and, in turn, social unrest.[104] A Stanford-based study found that as a result of a rise in mean temperatures the probability of a 30-day delay in the onset of Indonesia's annual monsoon will rise from 9–18 per cent in 2007 to 30–40 per cent in 2050.[105] This indicates "a need for adaptation strategies in Indonesian rice agriculture, including increased investments in water storage, drought-tolerant crops, crop diversification, and early warning systems."[106]

100 Climate Change Profile Indonesia (2018) Ministry of Foreign Affairs of the Netherlands.
101 Climate Risk and Adaptation: Country Profile for Indonesia. (2011). World Bank.
102 World Bank, World Development Indicators.
103 Ibid.
104 Caruso, R., Petrarca, I., & Ricciuti, R. (2016). Climate change, rice crops, and violence: Evidence from Indonesia. Journal of Peace Research, 53(1), 66-83.
105 Naylor, R. L., Battisti, D. S., Vimont, D. J., Falcon, W. P., & Burke, M. B. (2007). Assessing risks of climate variability and climate change for Indonesian rice agriculture. Proceedings of the National Academy of Sciences, 104(19), 7752-7757.
106 Ibid.

A rising sea level will also disrupt coastal fish and prawn farming.[107] Indonesia is expected to experience some of the world's steepest declines in marine fish stocks – a fall of almost 30 per cent by mid-century under a 'worst-case' climate change scenario.[108] Since a large part of the Indonesian diet is fish protein, this will have negative implications for both food security and health.[109] The second-order effects on health and workforce productivity are most likely to be large and negative, unless adaptive action is taken.

Finally, a warming climate will further threaten Indonesia's forests.[110] Not only are Indonesia's forests a key sources of biodiversity, they are also critical resources for the country and the entire world. Indonesia's indigenous forests are the source of many discoveries in the field of medicine. Changes in land use, temperature and precipitation have caused widespread wildfires in Indonesia that have altered forest composition and structure.[111] These fires have increased air pollution to dangerous levels, further negatively affecting human health and productivity.

1.2.5 Mexico

Mexico is exposed to several climatic risks which threaten its infrastructure, workforce productivity and agriculture. Mexico has over 11,000 kilometres of coastline, which is at risk from rising sea levels. The Yucatan Peninsula and the Caribbean coast are especially exposed to the economic effects of climate change as they have critical infrastructure such as hotels, roads, airports and ports that can be easily damaged by flooding events. These coastlines support much of Mexico's tourism industry, which faces an existential risk unless adaptive measures are implemented.[112] Secondly, the Gulf of Mexico is home to eight major fishing ports and two industrial ports.[113] Increased incidence of extreme weather events will hurt these major economic hubs. Ocean acidification also presents a threat to fisheries in the area. The other major infrastructure risk is drought. Hydroelectric plants, particularly in the northern parts of Mexico, are likely to see lower production levels if water sources start to dry up.[114] Heatwaves, particularly in densely populated urban centres such as Mexico City, are already starting to strain the power system as users demand more air conditioning. This puts power plants under stress. Making matters worse, power plants work less efficiently under higher temperatures.[115]

107 Climate Change Profile Indonesia (2018) Ministry of Foreign Affairs of the Netherlands.
108 Barange et al. (2018) Impacts of climate change on fisheries and aquaculture. FAO.
109 Indonesia, Climate Vulnerability Profile. (2012) USAID.
110 Ibid.
111 Ibid.
112 Union of Concerned Scientists' Climate Hot Map for Cancún, Mexico. Available at https://www.climatehotmap.org/global-warming-locations/cancun-mexico.html
113 USAID (2017) Climate Risk Profile: Mexico.
114 Ibid.
115 Ibid.

Workforce productivity in Mexico is another key variable that is affected by weather fluctuations. Extreme weather directly contributes to higher mortality rates.[116] Those who are worst hit tend to be from the lowest income groups. Specifically, nearly 5 per cent of deaths in Mexico (approximately 30,000 every year) are linked to weather extremes, mostly among the poor. [117] Experts predict that climate change will make winters colder, and summers hotter, exacerbating the pressure on Mexico's health systems. Improvements in healthcare policy in Mexico have saved thousands of lives every year from cold weather.[118] The implication is that in the future, healthcare systems will have to be better equipped and expanded to deal with new weather patterns.

Climate change also affects Mexico's labour productivity. There is a rich literature on how higher temperatures reduce the productivity of workers and the economy on the whole.[119] The relationship between economic productivity and temperature is non-linear for all countries, with productivity peaking at an annual average temperature of 13°C.[120] In the case of Mexico, the evidence shows that frequent heatwaves lead to a reduction in local employment, particularly for lower-wage work and non-farm labour. It also increases internal migration from rural to urban areas, and emigration to the US.[121] An increase in emigration could be particularly damaging for Mexico if it means the country loses otherwise productive labourers.

Agriculture in Mexico is also vulnerable to climate change. Production of coffee, an economically important cash crop, is projected to decline as droughts become more frequent.[122] The economic impact of this decline on farmers is not clear: on one hand, prices may increase, which could offset lower production volumes. On the other hand, prices could remain stable, in which case coffee growers will lose revenue.

116 Cohen, F., & Dechezleprêtre, A. (2020). Mortality, temperature, and public health provision: evidence from Mexico.
117 Ibid.
118 Ibid.
119 Burke, M., Hsiang, S. M., & Miguel, E. (2015). Global non-linear effect of temperature on economic production. Nature, 527(7577), 235-239.
120 Ibid.
121 Jessoe, K., Manning, D. T., & Taylor, J. E. (2018). Climate change and labour allocation in rural Mexico: evidence from annual fluctuations in weather. The Economic Journal, 128(608), 230-261.
122 Gay, C., Estrada, F., Conde, C., Eakin, H., & Villers, L. (2006). Potential impacts of climate change on agriculture: A case of study of coffee production in Veracruz, Mexico. Climatic Change, 79(3-4), 259-288.

Declines in agricultural productivity will also lead to emigration. According to one estimate, by 2080, climate change will induce 1.4 to 6.7 million adult Mexicans (or 2 per cent to 10 per cent of the current working-age population) to emigrate as a result of declines in agricultural productivity alone.[123]

1.2.6. Russia

The consensus view is that Russia stands to reap economic dividends from climate change. For example, melting ice caps in the Arctic will make the Russian coastline more navigable, which can open up new shipping routes and make it easier to exploit natural resources in the region.[124] Furthermore, changes in the climate will make previously inhospitable areas in the most northern latitudes suitable for agriculture and tourism. Our modelling of the overall economic impacts suggests an overall increase in GDP per capita for Russia in all the warming scenarios (compared to baseline). However, as explained in the Appendix, our approach does not account for the impact that economic declines in the rest of the world might have on the demand for Russian goods. (This also means that negative impacts found in other regions are likely to be more severe than modelled in this paper.)

While these positive impacts are expected, climate change is also likely to bring about upheaval. The latest evidence from academic research and government documents[125] points to major disruptions, especially because Russia is warming 2.5 times faster than the global average, as government officials have themselves acknowledged.[126]

The first major disruption would be to infrastructure.[127] The thawing of arctic permafrost threatens the foundations of many buildings and roads.[128] As recently reported, "rising temperatures have already begun to melt the permafrost, opening up vast craters and damaging apartment blocks, whose foundations depend on the frozen soil. It has also been partially blamed for the wildfires that engulfed more than 12 million hectares of Russian forest [in the

123 Feng, S., Krueger, A. B., & Oppenheimer, M. (2010). Linkages among climate change, crop yields and Mexico–US cross-border migration. Proceedings of the National Academy of Sciences, 107(32), 14257-14262.

124 Perelet, R., Pegov, S., & Yulkin, M. (2007). Climate change. Russia country paper. Background paper for the UN, 2008.

125 Dronin, N., & Kirilenko, A. (2011). Climate change, food stress, and security in Russia. Regional Environmental Change, 11(1), 167-178.

126 Foy, H. (2019). Russian Arctic leader warns of 'dramatic' climate change impact. Financial Times.

127 Perelet, R., Pegov, S., & Yulkin, M. (2007). Climate change. Russia country paper. Background paper for the UN, 2008.

128 Ibid.

summer of 2019] in Yakutia and elsewhere in Siberia."[129] Flooding is also a significant risk. The Lena River in Siberia — one of the longest rivers in the world — is experiencing more flooding due to climate change. Previous flooding along the river has cost around USD250 million in damages to economic assets and property.[130]

The second major disruption concerns food production and distribution.[131] Because of extreme weather events and more frequent droughts, there will be more food production shortfalls, defined as instances when the production of the most important crops in a region falls below 50 per cent of its usual average.[132] The frequency of food shortages could also double in major crop-growing areas in the 2020s and triple by 2070.[133] Agriculture is likely to be most severely affected in areas such as Yakutia, which is already experiencing increased dryness and droughts.[134]

There are also low-probability, high-impact risks which are less well understood, such as the spread of severe diseases due to warming because disease vectors shift further north.[135] As temperatures rise, migratory animals will survive longer and move further north, bringing new viruses to areas that were previously unexposed. Research highlights that the "the Russian Arctic should be viewed in context of an unfavourable epidemiologic situation."[136] It will be necessary for Russia to have "strengthened epidemiologic surveillance"[137] and be particularly vigilant of diseases such as anthrax.

1.2.7. South Africa

South Africa will become significantly hotter and drier due to climate change. By the end of the century, the country could experience an additional 17 extremely hot days (>35°C) every year if emissions peak in 2040 (the 'current policies' scenario), and potentially up to 46 extremely hot days if emissions rise throughout the 21st century (under the pessimistic, 'worst-case' climate scenario).[138] Average summer temperatures could be 2-4°C warmer depending on when emissions peak.[139]

129 Foy, H. (2019). Russian Arctic leader warns of 'dramatic' climate change impact. Financial Times.
130 Perelet, R., Pegov, S., & Yulkin, M. (2007). Climate change. Russia country paper. Background paper for the UN, 2008.
131 Dronin, N., & Kirilenko, A. (2011). Climate change, food stress, and security in Russia. Regional Environmental Change, 11(1), 167-178
132 Ibid.
133 Ibid.
134 Perelet, R., Pegov, S., & Yulkin, M. (2007). Climate change. Russia country paper. Background paper for the UN, 2008.
135 Revich, B., Tokarevich, N., & Parkinson, A. J. (2012). Climate change and zoonotic infections in the Russian Arctic. International journal of circumpolar health, 71(1), 18792.
136 Ibid.
137 Ibid.
138 Climate Impact Lab (2020). Climate Impact Map. Available at: http://www.impactlab.org/map (last consulted 7 September 2020.
139 Ibid.

Climate change will exacerbate water scarcity in South Africa, weighing on energy production. South Africa is situated within a drought belt and has an economy that is highly dependent on water resources.[140] Water plays an integral role in the power sector. Eskom, South Africa's public utility, supplies 95 per cent of the nation's electricity and in 2011 used 327 million cubic meters to produce it, which is equivalent to about 2 per cent of South Africa's water supply from current infrastructure.[141, 142] South Africa has a large domestic coal sector in which water is used to wash the coal and to cool powerplants. South Africa is already projected to see a 17 per cent gap between water supply and demand by 2030 equivalent to a shortfall of 2.7 billion cubic metres.[143] Climate change will increase the frequency of droughts and make water scarcity more acute.

Moreover, increased temperature and lower precipitation levels will affect South African agriculture. Vulnerable regions such as Limpopo, Kwazulu-Natal and the Eastern Cape have densely populated rural areas with large numbers of small-scale farmers who depend on rain-fed agriculture.[144] Climate change presents an existential risk to such people's livelihoods. Additionally, 70 per cent of South Africa's cereal crops and 90 per cent of commercially grown maize is cultivated in the Highveld region of South Africa.[145] The western part of this region already suffers from low precipitation and highly variable yields, which means its predicament will become more serious if current climatic trends continue.[146] The economic costs are likely to be significant: as one study explains, "for South Africa to adapt to the adverse consequences of climate change, it would require yield improvements of more than 20 per cent over baseline investments in agricultural research and development. Even a doubling of irrigation development will not be sufficient to reverse the adverse impacts from climate change in the country."[147] Rising food prices are a likely outcome unless proper adaptation efforts are undertaken.

140 UNDP (2020). Adaptation to Climate Change. Accessible from: https://www.adaptation-undp.org/explore/southern-africa/south-africa

141 Eskom Integrated Annual Report 2011 cited in Groenewald, Y. (2012). Coal's hidden water cost to South Africa. Greenpeace. Report.

142 Greencape. 2020. Water – 2019 Market Intelligence Report.

143 Groenewald, Y. (2012). Coal's hidden water cost to South Africa. Greenpeace. Report.

144 Gbetibouo, G. A., Ringler, C., & Hassan, R. (2010). Vulnerability of the South African farming sector to climate change and variability: an indicator approach. In Natural Resources Forum (Vol. 34, No. 3, pp. 175-187). Oxford, UK: Blackwell Publishing Ltd.

145 Walker, N. J., & Schulze, R. E. (2008). Climate change impacts on agro-ecosystem sustainability across three climate regions in the maize belt of South Africa. Agriculture, ecosystems & environment, 124(1-2), 114-124.

146 Ibid.

147 Calzadilla, A., Zhu, T., Rehdanz, K., Tol, R. S., & Ringler, C. (2014). Climate change and agriculture: Impacts and adaptation options in South Africa. Water Resources and Economics, 5, 24-48.

Climate change also brings other risks such as an increased disease burden and a possible rise in the number of wildfires. Diseases such as malaria and schistosomiasis are prevalent in South Africa. Temperature increases and changes in rainfall could potentially extend the areas prone to these diseases.[148] Furthermore, wildfires caused by droughts are likely to occur more frequently in the Fynbos region because of climate change.[149] Climate change research shows that South Africa can expect hotter and drier winds in the interior, increased rates of evapotranspiration, and a higher quantity of combustible biomass due to more carbon uptake in vegetation, each of which increasing the risks of large-scale wildfires.[150] Wildfires will impact not only local ecosystems and biodiversity, but also the tourism that these natural biomes attract.

148 UNDP (2020). Adaptation to Climate Change. Accessible: https://www.adaptation-undp.org/explore/southern-africa/south-africa
149 Ibid.
150 Ibid.

1.3 Sector-level evidence

The country-level evidence lays bare how local economies will be affected by climate change. Below, we provide additional information on two industrial sectors that simultaneously form the backbone of the global economy and are particularly vulnerable to climate change: power and agriculture.

1.3.1. Power sector

In the next few decades, the power sector will have to produce more energy, while at the same time slash its greenhouse gas emissions. Worldwide energy demand is expected to increase by at least 50 per cent in 2050 relative to 2018 according to the US Energy Information Administration (EIA).[151] Much of this increase will be driven by India and China, the world's fastest-growing economies. While Chinese demand is likely to taper as its economy pivots towards services, India is expected to see industrial energy consumption treble by 2050.[152] This rapid increase in demand also reflects a projected increase in income levels across the emerging world. In many emerging markets, rising incomes will mean first-time purchases of energy-intensive durable appliances such as television sets, refrigerators and air conditioners.[153] The challenge now is to simultaneously provide energy to those who most need it while engaging in deep decarbonisation, all without jeopardising security of supply. This will not be easy since, for a 50 per cent probability of limiting warming to 2°C, investments in unabated fossil fuel-based electricity infrastructure (i.e. without carbon capture and storage) would have needed to be halted in 2017, if they are going to avoid being prematurely "stranded".[154] However, in 2018, 30 per cent of new electricity generation capacity was still fossil fuel-based capital.[155] The electricity system needs to quickly pivot towards low-carbon technologies at large scale and simultaneously achieve greater levels of efficiency.

Climate change will thus add to the challenges that the electricity sector already faces, not least as it affects water supplies. Water is needed for most types of electricity generation, but it is also a resource that will be impacted by climate change. This vulnerability applies to both advanced nations and emerging markets alike. A study in *Nature Climate Change* points out that "power plants that require cooling currently provide 85 per cent of electricity

151 EIA (2019) International Energy Outlook.
152 Ibid.
153 Wolfram, Catherine, Orie Shelef, and Paul Gertler. 2012. "How Will Energy Demand Develop in the Developing World?" Journal of Economic Perspectives, 26 (1): 119-38.
154 Pfeiffer, A., Millar, R., Hepburn, C., & Beinhocker, E. (2016). "The '2°C capital stock' for electricity generation: Committed cumulative carbon emissions from the electricity generation sector and the transition to a green economy." Applied Energy, 179, 1395-1408.
155 REN21 (2018). "Renewables 2018 Global Status Report", Renewable Energy Policy Network for the 21st Century.

generation in the United States (2015). These facilities need large volumes of water and projected climate conditions may lower their potential power output and affect reliability."[156]

Hydropower generation depends directly on the availability of water resources, which will be affected by climate change. In many areas of the world, hydrological cycles are changing due to global warming. For example, many glaciers in the Andes have shrunk dramatically. Hydropower plants in these regions depend on the seasonal cycle of snowmelt to ensure regular output throughout the year.[157] However, with rapid melting and an overall reduction in glacier size, hydroelectricity is now threatened.[158]

Similarly, thermal power plants require significant amounts of water for cooling, making them vulnerable to fluctuations in water supply. Coal, natural gas, nuclear, geothermal and biomass residues are all energy sources that use thermal power plants for electricity production. Each unit of electricity generated via steam cycle requires around 90–100 litres of water.[159] Dry summers in the past few years have forced several thermoelectric power plants in Europe and south-eastern US to reduce production because of cooling-water scarcity.[160] Since almost all climate change scenarios indicate there will be lower availability of water in some regions, it is quite likely that power plants will increasingly compete with other water users such as agriculture and cities in water-stressed areas.[161] Air-cooled thermal plants may provide a way to overcome this problem but the deployment of such plants is currently limited and concerns around changes in efficiency will have to be addressed.

Changes in temperature could also affect the power sector. The operational efficiency of plants can be profoundly impaired by rising temperatures. For example, increasing temperature can impact the performance of gas turbines, leading to a decrease in generation or a higher fuel consumption.[162] Furthermore, the efficiency of the electricity transmission network, which can extend over thousands of kilometres, is dependent on weather conditions. As a power plant operator in the UK explains, "over-

156 Miara, A., Macknick, J., Vörösmarty, C. et al. Climate and water resource change impacts and adaptation potential for US power supply. Nature Clim Change 7, 793–798 (2017). https://doi.org/10.1038/nclimate3417
157 Schaeffe, R. et al. Energy sector vulnerability to climate change: a review. Energy 38, 1–12 (2012).
158 Ibid.
159 S.R. Bull, D.E. Bilello, J. Ekmann, M.J. Sale, D.K. Schamlzer. (2007). Effects of climate change on energy production and use in the United States. A Report by the U.S. Climate Change Science Program and the subcommittee on Global Change Research, Washington, DC
160 Van Vliet, M. T., Yearsley, J. R., Ludwig, F., Vögele, S., Lettenmaier, D. P., & Kabat, P. (2012). Vulnerability of US and European electricity supply to climate change. Nature Climate Change, 2(9), 676-681.
161 Schaeffe, R. et al. (2012). Energy sector vulnerability to climate change: a review. Energy 38, 1–12
162 Schaeffe, R. et al. (2012). Energy sector vulnerability to climate change: a review. Energy 38, 1–12

head power transmission cables are often clad in aluminium, which is particularly susceptible to expansion in heat. When it expands, overhead lines can slacken and sag, which increases electrical resistance in the cables, leading to a drop in efficiency."[163] Heatwaves can also contribute to electric transformer failures. Transformers radiate heat as a by-product of their operations. However, to keep them within a safe level of operation, they have a highest temperature at which they can safely function. When ambient temperatures rise, this ceiling drops, and the efficiency of transformers consequently falls.

Even solar power is not immune to climate change. Climate change will alter humidity and cloud cover, affecting levels of atmospheric transmissivity[164]. These changes will affect solar power in various ways around the world. Modelling suggests south-eastern Europe will see an increase in solar radiation by 6 per cent.[165] The Middle East is also likely to benefit from an increase in solar resources.[166] But in sub-Saharan Africa, solar radiation is expected to fall.[167] Moreover, hotter days increase electrical resistance. "Higher temperatures increase the electrical resistance of the circuits that convert the photovoltaic charge into AC electricity. Modern hybrid solar panels are designed to suffer less from the heat, but they can still lose 10 per cent of their rated efficiency on hot days."[168]

Climate change is exposing electricity infrastructure to higher levels of risk and new types of uncertainties.[169] The assumptions that informed the building of electricity infrastructure require revision. As extreme weather events become more commonplace and average temperatures rise, the electricity sector will be more vulnerable. As discussed in section 1.2.6, the thawing of permafrost in Russia is likely to undermine the foundations of many buildings and infrastructure projects there. Notably, it will impact Russia's gas transmission network, which will have spillover effects on countries that import Russian gas.[170] Likewise, a large share of emerging markets' electricity infrastructure has been built in areas that may be at increased risk of flooding because of climate change. A study in China finds that infrastructure assets in Anhui, Beijing, Guangdong, Hebei, Henan, Jiangsu, Liaoning, Shandong, Shang-

163 Drax (2020) "What hot weather means for electricity". Accessible: https://www.drax.com/technology/hot-weather-means-electricity/
164 Schaeffe, R. et al. (2012) Energy sector vulnerability to climate change: a review. Energy 38, 1–12.
165 Ibid.
166 Ibid.
167 Ibid.
168 Villazon, Luis. (2020) Do solar panels work better on hot days? Science Focus.
169 Audinet P., Amado JC., Rabb B. (2014) Climate Risk Management Approaches in the Electricity Sector: Lessons from Early Adapters. In: Troccoli A., Dubus L., Haupt S. (eds) Weather Matters for Energy. Springer, New York, NY.
170 Schaeffe, R. et al. (2012) Energy sector vulnerability to climate change: a review. Energy 38, 1–12.

hai, Tianjin and Zhejiang are exceptionally exposed to flooding.[171] Some 103 million Chinese are likely to be affected by the impact of flooding on infrastructure. The most exposed sub-sectors are electricity and wastewater.[172]

In addition, climate change will increase the demand for cooling. The impact of climate change on electricity consumption depends to a great extent on whether a region is cold, or already warm. In colder areas, climate change will reduce the need for heating, and therefore reduce consumption of gas, electricity, and fuel oil for heating. However, in warmer areas, temperature rises will increase demand for cooling and, therefore, energy. In the US, researchers have found a clear U-shape relationship between energy demand and temperature, with an extra day below -12°C or above 32°C raising annual energy demand by 0.3–0.4 per cent.[173] In many emerging markets, the incidence of extremely hot days (those on which temperatures reach at least 35°C) will go up significantly due to climate change (see section 1.2). One study finds that mean annual temperatures in Thailand will rise by 1.74 to 3.43°C by 2080, implying increases in Thai peak electricity demand of 1.5-3.1 per cent in the 2020s, 3.7-8.3 per cent in the 2050s, and 6.6-15.3 per cent in the 2080s.[174] This will put pressure on power systems in emerging markets, over and above that which is already generated by rapid economic growth and population increase.[175]

All in all, climate change poses serious risks to energy security in emerging markets. Large-scale physical damage due to extreme weather, disputes between countries that share threatened hydropower resources, such as India and Pakistan, and the increased need for cooling as summer temperatures soar will threaten security of supply in emerging markets. India already has a 'quality of supply' problem: even though the supply of electricity is currently enough to meet demand, the poor financial health of state utilities means that these entities cannot always afford to purchase power and resort to load-shedding. Moreover, many villages continue to have very limited supply. As India's economy rapidly expands, and its population increases and climbs out of poverty, the country's demand for

171 Hu, X., Hall, J. W., Shi, P., & Lim, W. H. (2016). The spatial exposure of the Chinese infrastructure system to flooding and drought hazards. Natural Hazards, 80(2), 1083-1118.

172 Ibid.

173 Deschênes, O., & Greenstone, M. (2011). Climate change, mortality, and adaptation: Evidence from annual fluctuations in weather in the US. American Economic Journal: Applied Economics, 3(4), 152-85.

174 S. Parkpoom and G. P. Harrison, (2008) Analyzing the Impact of Climate Change on Future Electricity Demand in Thailand, in IEEE Transactions on Power Systems, vol. 23, no. 3, pp. 1441-1448.

175 Dell, M., Jones, B. F., & Olken, B. A. (2014). What do we learn from the weather? The new climate-economy literature. Journal of Economic Literature, 52(3), 740-98.

electricity will rise, at which point supply will also have to keep up. But cascading hazards (i.e. situations where one extreme event precipitates another extreme event) are becoming a major concern for energy infrastructure.[176] A cascading hazard was responsible for Japan's nuclear meltdown as the earthquake first shut off electricity and thereafter the tsunami destroyed the back-up generators. Much of South Asia depends critically on shared hydropower resources, particularly India, Pakistan, Bhutan, Nepal and Bangladesh, but research predicts declines of hydropower capacity of up to 6 per cent under the 'worst-case' warming scenario in the 2080s.[177]

The energy sector has the greatest exposure to transition risk of any sector. As detailed in section 1.2, the electricity and industrial sectors hold a disproportionate amount of committed emissions, representing some 75 per cent of total committed emissions. At the same time, however, they represent just 25 per cent of the globe's total assets. (Fig. 3). That is a crucial disparity when it comes to combating climate change because it means electricity assets are the most cost effective to strand first under ambitious mitigation policies. Further, as discussed below in section 2.1, cost improvements in renewable energy-generation technologies, such as solar, wind and storage, are already putting ever-increasing pressure on fossil energy assets, to the point that it is becoming economically profitable in different locations to close fossil energy assets early and replace them with renewables.

Solutions need to be found to secure power supplies. All existing infrastructure needs to be climate-proofed: detailed risk assessments are needed to evaluate how current infrastructure would handle heat stress and extreme weather events. Meanwhile, system-level planning is required to ensure that the grid can guarantee security of supply: while renewable energy can help stave off energy imports for those nations that do not have domestic fossil fuel reserves, the supply of electricity from renewables is intermittent. However, this intermittency can be an opportunity to develop grids that are 'smart' and more efficient. Infrastructure that can store and supply excess renewable power can be used to smooth out peaks and troughs in electricity supply across regions. Demand-side management, such as time-of-day pricing, can be also deployed to

176 Moftakhari, H., & AghaKouchak, A. (2019). Increasing exposure of energy infrastructure to compound hazards: cascading wildfires and extreme rainfall. Environmental Research Letters, 14(10), 104018.

177 Cronin, J., Anandarajah, G., & Dessens, O. (2018). Climate change impacts on the energy system: a review of trends and gaps. Climatic change, 151(2), 79-93.

ensure consumers adjust their needs to match available supply. And a host of energy-storage solutions, ranging from tried and tested hydro-pumped storage to more modern-day batteries, can help the system balance. It is also possible to develop new, zero-carbon energy vectors (e.g. molecules that carry energy, such as hydrogen) and technologies to ensure security of supply. For instance, green ammonia and hydrogen could in future provide cheap, large-scale storage and means of transporting energy long distances around the world.[178]

Adaptive measures for current infrastructure could also reduce the impact of rising temperatures, water shortages and extreme weather events on the electricity system. Four recommendations from an extensive study on the interlinkages between climate, water and energy stand out. They are:

— “Joint efforts between the electricity sector and hydro-meteorological offices to develop high-quality and tailored climate data and information are needed to avoid ‘wait-and-see’ strategies among power utilities;
— energy-sector adaptation requires going beyond high-level research on impacts and adaptation to produce information that can be applied operationally;
— without a business environment favourable to climate change adaptation, power utilities have little incentive to go beyond ‘business-as-usual’ weather risk management;
— it is by building the economic case for adaptation that utilities can be incentivised to take action.”[179]

With these measures, the electricity system of today could be safeguarded while ways are found to build the system of tomorrow.

178 IEA, The Future of Hydrogen: Seizing today’s opportunities, G20 in Japan, 2019.
179 Troccoli, A., Dubus, L., & Haupt, S. E. (Eds.). (2014). Weather matters for energy. Berlin: Springer.

1.3.2. Agriculture

Feeding a growing global population while contending with a changing climate is immensely challenging.[180] To meet the needs of a world population which is expected to peak at 8.5–10 billion in 2050, grain production must increase by at least 50 per cent.[181] Agricultural production depends on weather, and climate change has the potential to have a significant impact on the sector's productivity.[182] Much of the increase in food demand is likely to arise over the next two decades – after 2050, demand is expected to slow.[183]

Which means small changes in the world's climate in the next few years are likely to have as big an effect on food prices and food security as the more serious environmental changes predicted in the second half of the century.[184]

Although climate change will affect agriculture in many different ways, overall worldwide food production is expected to be disrupted. Our modelling suggests a net decline in global GDP per capita for agriculture under all the warming scenarios and for most of the emerging economies (compared to baseline and in isolation).[185] The precise channels through which climate change may impact agriculture are diverse. Increasing CO_2 concentrations can increase plant productivity. But at the same time rising temperatures can increase water scarcity and dry out once fertile soils. Latitude also plays a role. Climate change can open up opportunities for agriculture in some regions and disrupt it in others. Nevertheless, food production and yields are expected to decline worldwide.[186] Furthermore, there is the real risk of catastrophic changes due to climate change, such as the collapse of the monsoon weather system, which would severely impact South Asian agriculture, or the collapse of historical rainfall patterns in the Amazon forest.

180 Challinor, A. J., Watson, J., Lobell, D. B., Howden, S. M., Smith, D. R., & Chhetri, N. (2014). A meta-analysis of crop yield under climate change and adaptation. Nature Climate Change, 4(4), 287-291.

181 Meng, Q., Chen, X., Lobell, D. B., Cui, Z., Zhang, Y., Yang, H., & Zhang, F. (2016). Growing sensitivity of maize to water scarcity under climate change. Scientific reports, 6, 19605.

182 Auffhammer, Maximilian, and Wolfram Schlenker. "Empirical studies on agricultural impacts and adaptation." Energy Economics 46 (2014): 555-561.

183 Lobell, D. B., & Tebaldi, C. (2014). Getting caught with our plants down: the risks of a global crop yield slowdown from climate trends in the next two decades. Environmental Research Letters, 9(7), 074003.

184 Ibid.

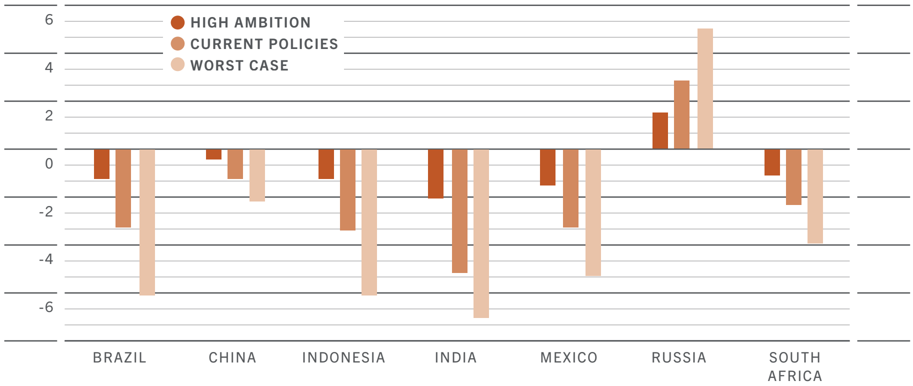
185 The estimated increase in GDP per capita for Russia does not account for the impact that economic declines in the rest of the world might have on the Russian economy and demand for Russian goods.

186 Liu, Bing, Senthold Asseng, Christoph Müller, Frank Ewert, Joshua Elliott, David B. Lobell, Pierre Martre et al. (2016) Similar estimates of temperature impacts on global wheat yield by three independent methods Nature Climate Change 6, no. 12: 1130-1136.

The impact of climate change on agriculture will affect a substantial portion of the emerging market labour force. As Figs. 6 and 7 show, in many emerging markets, such as India, a large proportion of the labour force depends on agriculture and will be adversely affected by climate change. Many of these workers are among the poorest and most vulnerable people in the world.

FIG.6

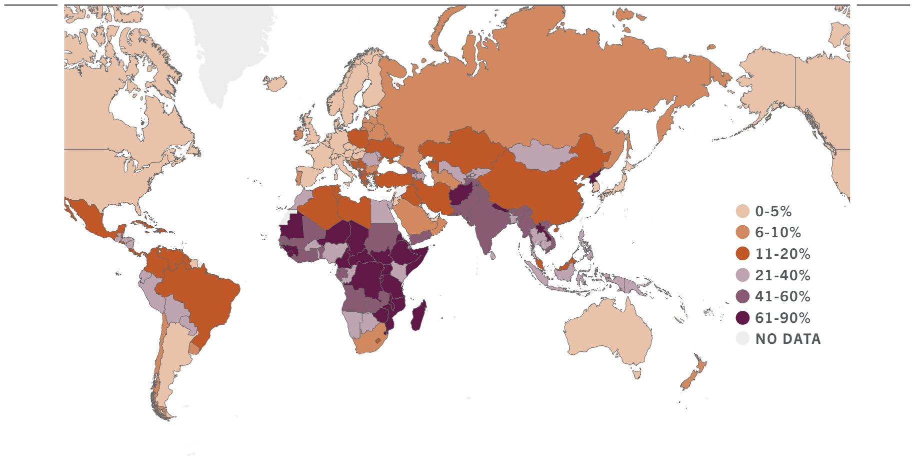
CLIMATE IMPACT ON AGRICULTURAL GDP PER CAPITA, % ANNUAL GROWTH IMPACT IN 2100 UNDER THREE DIFFERENT WARMING SCENARIOS



Source: this report

FIG.7

SHARE OF LABOUR FORCE EMPLOYED IN AGRICULTURE IN 2017, % OF TOTAL EMPLOYMENT



Source: World Bank, Our World in Data. Modelled ILO estimate

Wheat, maize, rice, corn and soybean are the main sources of human and livestock calories globally, and their production will also be affected by climate change.[187] For wheat, a 1°C increase in the global mean temperature is expected to reduce global yields by 4 to 6 per cent.[188] For maize, production must roughly double, in the midst of a changing climate, to meet the growing demand for food, biofuel and livestock feed.[189] Some regions will be worse affected than others. Of the land devoted to growing maize in China, 40 per cent now fails to receive the precipitation required to attain the full yield potential.[190] In Africa, researchers looked at the effect of degree days over 30°C on agriculture yields. Degree days (a measure of heating over time) are obtained by taking the average temperature of every day and adding up each degree over 30°C for each day. For example, an area would record 365 degree-days over 30°C if its average temperature were 31°C all year round (31 – 30 degrees, multiplied by 365 days). In Africa, researchers found that each degree day above 30°C reduced the final yield of maize by 1 per cent under optimal rain-fed conditions, and by 1.7 per cent under drought conditions.[191] Even advanced agriculture markets are not immune. A study on the non-linear impacts of temperature in the US finds that yields increase with temperature up to 29°C for corn, 30°C for soybeans, but temperatures above these thresholds are very harmful.[192] The scale of gains obtained with every degree increase approaching these thresholds is significantly smaller than the rate at which yield collapses once these thresholds are breached. To put this into context, some of America's main corn-producing states like Iowa and Missouri will experience 19 to 29 extra extremely hot days (those on which temperatures reach at least 35°C), respectively, by mid-century in a pessimistic 'worst-case' scenario and 10 to 19 extra days if global emissions peak by 2040 – the 'current policies' scenario.[193] This will severely and negatively impact corn yields because fields cannot support production at these very high temperatures.

187 Lobell, D. B., & Gourdji, S. M. (2012). The influence of climate change on global crop productivity. Plant physiology, 160(4), 1686-1697.

188 Liu, Bing, Senthold Asseng, Christoph Müller, Frank Ewert, Joshua Elliott, David B. Lobell, Pierre Martre et al. (2016): Similar estimates of temperature impacts on global wheat yield by three independent methods. Nature Climate Change 6, no. 12 1130-1136.

189 Lobell, D. B., & Gourdji, S. M. (2012). The influence of climate change on global crop productivity. Plant physiology, 160(4), 1686-1697.

190 Meng, Q., Chen, X., Lobell, D. B., Cui, Z., Zhang, Y., Yang, H., & Zhang, F. (2016). Growing sensitivity of maize to water scarcity under climate change. Scientific reports, 6, 19605.

191 Lobell, D. B., Bänziger, M., Magorokosho, C., & Vivek, B. (2011). Nonlinear heat effects on African maize as evidenced by historical yield trials. Nature Climate Change, 1(1), 42-45.

192 Schlenker, W., & Roberts, M. J. (2009). Nonlinear temperature effects indicate severe damages to US crop yields under climate change. Proceedings of the National Academy of Sciences, 106(37), 15594-15598.

193 Climate Impacts Lab http://www.impactlab.org/

Rice is a staple in Asia and any climate-induced deterioration of rice production would have a serious impact on food security and on livelihoods across the continent, unless there is robust adaptation.[194] "The mega-deltas in Vietnam, Myanmar and Bangladesh, the backbone of these countries' rice economies, will experience specific and adverse climate change impacts due to sea-level rise. The other 'hotspot' with especially high climate change risks in Asia is the Indo-Gangetic Plains, which will be affected by the melting of the Himalayan glaciers."[195] Significant improvements such as higher resilience to flooding and salinity, and effective crop rotation cycles will be needed to mitigate these impacts.[196]

Climate change also increases the risk of crop failures, which would have knock-on impacts on the cost of insurance. There is now evidence showing that because of global warming, the chance of a 10 per cent yield loss over the next 20 years has increased from less than 1 in 200 to a 1 in 10 chance for maize and 1 in 20 chance for wheat.[197] This will affect the cost of finance and insurance for agriculture.

Thus far, even adaptation in advanced economies has not yet shielded agriculture from the full breadth of climatic impacts. A prominent study surveyed large variations in temperature and precipitation trends to identify adaptive responses to climate change in US agriculture. It found that longer-run adaptations appear to have mitigated less than half—and more likely none—of the large negative short-term effects of extreme heat on productivity. It concluded that the evidence of limited recent adaptation implies substantial losses under future climate change in the absence of countervailing investments.[198] Geospatial vulnerability assessments may become crucial for planning targeted and effective adaptation programmes.[199]

194 Wassmann, R., Jagadish, S.V.K., Sumfleth, K., Pathak, H., Howell, G., Ismail, A., Serraj, R., Redona, E., Singh, R.K. and Heuer, S., (2009). Regional vulnerability of climate change impacts on Asian rice production and scope for adaptation. Advances in agronomy, 102, pp.91-133.

195 Ibid.

196 Ibid.

197 Lobell, D. B., & Tebaldi, C. (2014). Getting caught with our plants down: the risks of a global crop yield slowdown from climate trends in the next two decades. Environmental Research Letters, 9(7), 074003.

198 Burke, Marshall, and Kyle Emerick. 2016. Adaptation to Climate Change: Evidence from US Agriculture. American Economic Journal: Economic Policy, 8 (3): 106-40.

199 Wassmann, R., Jagadish, S.V.K., Sumfleth, K., Pathak, H., Howell, G., Ismail, A., Serraj, R., Redona, E., Singh, R.K. and Heuer, S., (2009). Regional vulnerability of climate change impacts on Asian rice production and scope for adaptation. Advances in agronomy, 102, pp.91-133.

While the effects of climate change on the world's main staple crops have been researched extensively, more investigation is needed into other crops required for a healthy diet. "Many other foods are important sources of calories (e.g. starchy roots in Africa, non-soybean vegetable oils, and sugar) or protein (e.g. pulses and seafood). Yet there is relatively little known about the response of their production to climate change." [200] Some evidence points towards largely negative impacts – by mid-century in sub-Saharan Africa, aggregate cassava production will fall 8 per cent, sorghum and millet by 17 per cent, groundnut by 18 per cent and maize by 22 per cent. This will have significantly damaging effects on the region's food security, local livelihoods, and food prices.[201]

A wide range of exciting new technologies could make a difference in combating some of these adverse effects.[202] Artificial meats, solar foods, precision biology and precision fermentation each have significant commercial potential and are currently being explored. [203] If low-cost lab-grown meat can be produced at scale, it will bring enormous environmental benefits. It could reduce demand for agricultural land and cut methane emissions from animal husbandry and deforestation. More conventionally, technology to monitor on-farm conditions can give real-time alerts to farmers and improve farm management practices. This is a relatively low-cost and capital-light method of improving farm productivity. A field experiment on banana production in India found that such 'precision agriculture' techniques significantly improved yields and reduced farm management costs.[204] The experiment involved the installation of a wireless sensor network to capture real-time temperature, humidity, soil moisture and rainfall data across the plantation. This was merged with an app to give the user alerts about changing weather conditions, pest attacks and crop diseases.[205] As hypothesised, farm management did indeed improve because of the intervention. Such technology, coupled with satellite imagery, can also be deployed for better forest management and stewardship, helping protect some of the world's most important carbon sinks.

200 Lobell, D. B., & Gourdji, S. M. (2012). The influence of climate change on global crop productivity. Plant physiology, 160(4), 1686-1697.http://www.plantphysiol.org/content/160/4/1686

201 Schlenker, W., & Lobell, D. B. (2010). Robust negative impacts of climate change on African agriculture. Environmental Research Letters, 5(1), 014010.

202 Oxford Martin School (2019). Meat: the Future series Alternative Proteins. White paper prepared for the World Economic Forum.

203 Ibid.

204 S. Pujari and N. Bogiri, (2017) Precision Agriculture for Banana Using Wireless Sensor Network, International Conference on Computing, Communication, Control and Automation (ICCUBEA), Pune, pp. 1-6.

205 Ibid.

Finally, decentralised technologies such as desalination plants may also help mitigate water scarcity. Decentralised technologies that do not require large-scale networked infrastructure can help improve the quality and security of water supply. There is no shortage of saltwater on Earth, and desalination technologies have seen increased uptake, a decline in costs [206], and a reduction in carbon-intensity through the use of solar power.[207] The technological innovation in the field is advancing rapidly and includes the use of nanomaterials to aid the desalination process.[208]

206 Burn, S., Hoang, M., Zarzo, D., Olewniak, F., Campos, E., Bolto, B., & Barron, O. (2015). Desalination techniques—A review of the opportunities for desalination in agriculture. Desalination, 364, 2-16.

207 Jones, E., Qadir, M., van Vliet, M. T., Smakhtin, V., & Kang, S. M. (2019). The state of desalination and brine production: A global outlook. Science of the Total Environment, 657, 1343-1356.

208 Alabi, A., AlHajaj, A., Cseri, L., Szekely, G., Budd, P., & Zou, L. (2018). Review of nanomaterials-assisted ion exchange membranes for electromembrane desalination. npj Clean Water, 1(1), 1-22.

1805

Accelerating the green transition post Covid-19

Accelerating the green transition post Covid-19

Having presented the extent of the risks posed by climate change globally, and more specifically for emerging economies, we now discuss how the recovery from Covid-19 can speed efforts to mitigate climate change.

Key sectors will be severely disrupted by climate change unless they cut their emissions to net zero. Most emerging economies are particularly at risk because they tend to be in warmer areas of the planet. Large shares of their populations are vulnerable. Those that rely on subsistence agriculture will be the first hit, but so too will those that do not have the financial means to adapt and live in areas exposed to increasingly frequent heatwaves, droughts, and floods.

What happens during this decade will be critical to whether we can avoid catastrophic climate change. That the 20s have opened with a global health crisis and its major economic implications raises special challenges but also creates new opportunities. Governments are investing massively in rescuing and rebooting their economies. This affords a unique chance to invest heavily in the low-carbon transition and build economies back in a better way. Investors, accordingly, need to look for the new opportunities that green markets could provide.

Low-carbon technologies are now commercially available and in continuous development. Large-scale deployment is achievable. Furthermore, international negotiations have made progress with the Paris Agreement, raising the hope that multilateral solutions will be found to accelerate the transition. One by one, countries are developing strategies to be competitive in a net-zero global economy, and, as they do so, developing an edge on key sectors such as solar, wind or bioenergy. In contrast, those that tend to rely the most on fossil fuels may lose heavily from the transition, as existing assets are stranded by increasingly unfavourable economics and as the world strives to avoid the worst of all climate change scenarios.

2.1. Political momentum for a green recovery from Covid-19

In a matter of weeks, the coronavirus crisis dramatically changed the world economy. To cushion an unprecedented global economic crisis, at the time of writing (July 2020) governments are investing in large-scale recovery packages. The European Union aims for a EUR750 billion recovery plan.[209] The US has made similar announcements, including a USD500 billion lending programme for large corporations,[210] while it has already lent USD350 billion to small and medium-sized enterprises (SMEs).[211] In emerging markets, China is expected to issue a special bonds programme worth more than USD700 billion,[212] while India announced a stimulus package worth more than USD 270 billion.[213]

While governments have focused on preventing their economies from collapsing, these recovery packages could also have substantial impacts on climate change. These recovery packages should be used to both minimise the economic damage caused by Covid-19 and to mitigate the ongoing climate emergency.[214] These packages could accelerate the transition away from fossil energy and make progress towards limiting warmth to the 2°C target of the Paris Agreement. The decisions that will be taken in the coming months will therefore be decisive for climate action.

209 Kahn, Mehreen (2020) Europe's capitals take aim at €750bn recovery plan, Financial Times, 7 June 2020.

210 Stein, Jeff and Whoriskey, Peter (2020) $500 billion bailout plan for large companies has no requirements to preserve jobs or limit executive pay, Stars and Stripes: https://www.stripes.com/news/us/500-billion-bailout-plan-for-large-companies-has-no-requirements-to-preserve-jobs-or-limit-executive-pay-1.627715

211 Popken, Ben (2020) Small-business loan program just hit its $350 billion cap and is now out of money. NBC News: https://www.nbcnews.com/business/business-news/small-business-loan-program-just-hit-its-350-billion-cap-n1185406

212 The Straits Times (2020) No flood of liquidity to spur Covid-19 recovery: China PM, 20 May 2020: https://www.straitstimes.com/asia/east-asia/no-flood-of-liquidity-to-spur-covid-19-recovery-china-pm

213 The Hindu Business Line (2020) A package for India's economic recovery, at last: https://www.thehindubusinessline.com/opinion/editorial/a-package-for-indias-economic-recovery-at-last/article31576280.ece

214 Hepburn, C., O'Callaghan, B., Stern, N., Stiglitz, J., & Zenghelis, D. (2020). Will Covid-19 fiscal recovery packages accelerate or retard progress on climate change?. Oxford Review of Economic Policy, 36.

In the past, many opportunities to act effectively on climate change were lost. In the 25 years preceding the Paris Agreement, national governments largely failed to coordinate on how to reduce emissions and tackle climate change because countries could not agree on what would constitute a fair way to divide the "burden" of emissions reductions. Talks which started in Kyoto in 1997 eventually collapsed in 2009 in Copenhagen. Policymakers realised that there was a critical need to introduce a new way of engaging in global climate negotiations without threatening the national sovereignty.

Then, in 2015, the Paris Agreement rebooted climate diplomacy, established a common climate goal and presented a mechanism by which more ambitious programmes could be introduced. Paris changed the logic of climate action. It gave countries the chance to submit their own voluntary climate targets in the form of Nationally Determined Contributions (NDCs), which are to be reviewed and scaled up every five years. Moving from top-down legally binding targets to bottom-up nationally determined contributions, Paris tried to ensure emissions reductions became an internally motivated ambition. The Paris Agreement had three main successes. All countries agreed to:

— Limit warming to well below 2°C, and pursue efforts for 1.5°C
— Achieve net-zero emissions by the second half of the century[215]
— A bottom-up systematic review process to increase ambition every five years

Some 195 states signed the agreement and, as of March 2020, 186 have ratified it, representing 97 per cent of global emissions. Every country submitted an NDC, and the most ambitious ones were able to clearly signal their commitment to decarbonise. Even the countries that submitted less ambitious NDCs could sense that the green transition had begun and that markets would begin to shift expectations. As of March 2020, two countries have achieved net-zero emissions (Bhutan and Suriname), five countries have net-zero targets enshrined in law (Sweden, United Kingdom, France, Denmark and New Zealand) and four governments have it as proposed legislation (European Union, Fiji, Spain and Chile).[216]

215 Specifically, it was agreed to "achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century" United Nations (2015). Paris Agreement.

216 Energy & Climate Intelligence Unit (2020) Net Zero Tracker. Accessed in March 2020. Available: https://eciu.net/netzerotracker

Furthermore, the United Nations has integrated climate action within the broader context of the Sustainable Development Goals (SDGs) and the 2030 Agenda for Sustainable Development. There is now a multilateral platform available for governments to discuss synergies and trade-offs between climate action and other goals and find ways to push for greater change. It is increasingly clear that climate goals align with poverty eradication, as the poor are the most vulnerable to climate impacts. In parallel, natural climate solutions, such as preventing deforestation and encouraging reforestation, have the potential to provide climate benefits and simultaneously boost ecosystem services that support economic livelihoods and development.

Before the pandemic there was already a groundswell of climate action by businesses, investors and other actors. As of January 2020, 778 companies had signed up to the Science Based Targets initiative (SBTi), which helps them set targets to reduce their emissions in a manner that is consistent with the goals of the Paris Agreement. Action is already visible: 100 of the world's largest companies, with USD3 trillion in purchasing power, reported emissions reductions equivalent to 551 million tonnes of CO_2 — more than Brazil's total emissions in 2016, with cost savings amounting to USD14 billion.[217] Large investment firms, such as BlackRock, are becoming increasingly vocal about climate risks to businesses.[218]

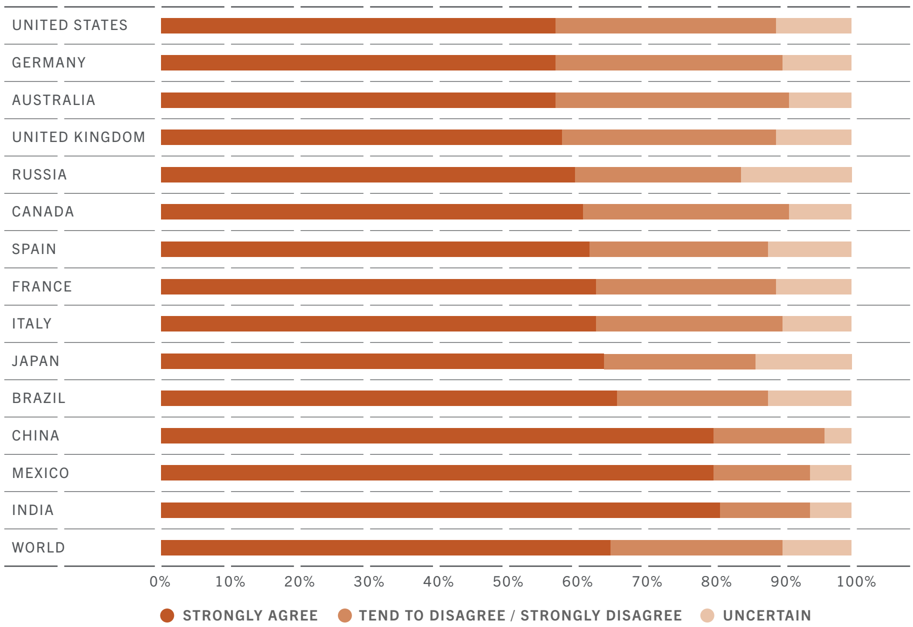
City-level climate action also gained momentum with the formation of large and powerful networks, featuring some of the largest emerging market cities. One of the most prominent networks is C40 Cities, which connects 94 major cities, including New York, Johannesburg, Beijing, Paris, New Delhi and Lagos. Representing over 700 million citizens and one quarter of the global economy, mayors of C40 cities have committed to delivering the goals of the Paris Agreement at the local level.[219] Examples of city-level initiatives in emerging markets include India's Smart Cities Mission, in which 100 smart cities will be developed with high-tech solutions like recycling, use of renewables and protection of sensitive natural environments.[220] In China, action includes Beijing's low emissions zone and the target of ensuring 50 per cent of buildings in newly built cities are green by 2020.[221]

217 Carbon Trust (2018). Corporate sustainability - learning from leaders. Blog post. Accessible: https://www.carbontrust.com/news-and-events/insights/corporate-sustainability-learning-from-leaders
218 BlackRock Investment Institute (2019). Getting physical: assessing climate risks. Blog post.
219 C40 Cities website: https://www.c40.org/ (last consulted on 7 September 2020)
220 India's Nationally Determined Contribution.
221 China's Nationally Determined Contribution.

There is significant support among voters in many countries, including emerging markets for making Covid recovery packages green. The EU has already taken significant action towards a green recovery. The EU has proposed to strengthen its Just Transition Fund up to EUR40 billion to accelerate the low-carbon transition. Above all, the allocation of the EUR310 billion of grants and EUR250 billion of loans of the European Recovery and Resilience Facility include sustainability as a core objective. This could be a game changer in the low-carbon transition, depending on how funds are ultimately allocated.[222] Likewise, the World Bank, which is an essential lender to emerging economies, has emphasised that sustainability will be an important component of their Covid-19 response.[223] Pressure is mounting for all governments to act. For example, 200 UK companies recently called on the British government to prioritise the environment in its recovery package.[224]

FIG.8

SUPPORT FOR A GREEN RECOVERY FROM COVID-19



Source: Ipsos Global Advisor, April 2020

222 European Commission (2020). Recovery Plan for Europe. Available at: https://ec.europa.eu/info/live-work-travel-eu/health/coronavirus-response/recovery-plan-europe_en

223 World Bank (2020). Covid-19 Intensifies the Urgency to Expand Sustainable Energy Solutions Worldwide, World Bank Press Release, 28 May 2020.

224 Roger Harrabin (2020), "Make Covid-19 recovery green, say business leaders", BBC News, 1 June 2020.

Emerging markets could also actively direct funds from recovery packages towards green industries and add conditionality to carbon-intensive sectors. This is a unique opportunity for emerging economies to funnel more investment into renewable energy, electric vehicles, energy efficiency and adaptive investments which can stimulate the economy. To meet the Paris goals, one option could be to require support offered to carbon-intensive sectors to come with "green conditionality". For example, bailouts to carbon-intensive industries, such as aviation, oil and gas, and automotive, could come with strings that require the industry to commit to carbon offsets, pay appropriate fuel taxes and invest in green research and development (e.g. green ammonia/hydrogen, synthetic kerosene or waste-based biofuels).

Governments in emerging economies have extended post-Covid support to industries that are both low-carbon as well as those that are high-carbon. In China, notable green stimulus initiatives included an expansion of subsidies to electric vehicles. At the same time, however, it relaxed environmental standards for industry and streamlined processes for obtaining coal-mining permits.[225] A significant portion of India's recovery package has been earmarked for coal. Over the next four years, India will spend USD13 billion on increasing coal production by 40 per cent. In Brazil, the lower house of the National Congress has just approved and sent to the Senate for approval a new law aiming at encouraging the production and distribution of natural gas. The law may liberalise the natural gas markets and reduce administrative barriers, with the aim of reducing the cost of energy and stimulate the economy.[226] Russia has given subsidies to its oil and gas sector without imposing any conditions on improving the efficiency of the sector, offsetting emissions or investing in negative emissions technologies. Overall, key emerging countries such as India, China, Russia, Indonesia and Mexico do not seem to be doing enough, for now, in pushing for green stimulus.[227]

Pledges for a Covid-19 green recovery should be accompanied by an update of the Nationally Determined Contributions (NDCs). The Parties of the Paris Agreement have committed to setting more ambitious NDCs. As of December 2019, the NDCs have only a 66 per cent or greater chance of limiting warming below 3.0°C.[228] By contrast, without any climate action, temperatures could reach 4.1°C – 4.8°C above pre-industrial level by the end of the

225 Vivid Economics and Finance for Biodiversity Initiative (2020) Green Stimulus Index.
226 Brazilian Parliament (2013). Projeito de lei 6407/2013 (accessible at: https://www.camara.leg.br/proposicoesWeb/fichadetramitacao?idProposicao=593065)
227 Vivid Economics and Finance for Biodiversity Initiative (2020) Green Stimulus Index.
228 Climate Action Tracker (2020). Temperatures. Accessible at: https://climateactiontracker.org/global/temperatures/

century.[229] The NDCs are therefore clear contributions to limiting global warming, but fall short of their objective of limiting warming below 2.0°C. However, the five-year ratchet process of the Paris Agreement could narrow these gaps. For example, in Brazil's NDC, the current target is to reduce GHG emissions by 37 per cent by 2025 relative to 2005, and the subsequent indicative target is to cut by 43 per cent below 2005 levels by 2030. The recovery packages provide an opportunity for governments to aim for more ambitious targets.

Using Covid-19 recovery programmes, emerging market economies can build upon the visions they already outlined for a new global low-carbon future. Out of all the NDCs, some of the loftiest visions for a new sustainable future came from emerging countries (see Table 3 for a summary of selected NDCs). For example, China's development plans have put forth precise policies to incentivise the growth of strategic green industries and cap the growth of domestic coal. India has similarly underscored the critical need for long-term sustainability and its vision to embrace new, clean technologies that would deliver both economic growth and climate mitigation. India is making rapid progress on its highly ambitious target to install 175 gigawatts of renewable energy capacity by 2022 – it is already a top five producer of wind energy. Both China and India's NDC texts go beyond simply listing targets by outlining a new vision for economic development, one in which the environment is respected. In fact, green industries can be strong drivers of growth (see section 3.3 on India and China's green industrial strategies).

TABLE 3

EMERGING MARKET CLIMATE COMMITMENTS

REGION	OVERALL EMISSIONS TARGET
CHINA	To lower the CO_2 emissions per unit of GDP by 60-65% by 2030 from the 2005 level
INDIA	To reduce the emissions intensity of GDP by 33-35% by 2030 from 2005
MEXICO	To reduce 25% of greenhouse gases by 2030 relative to business as usual (BAU)
SOUTH AFRICA	Emissions including land use, land-use change, and forestry (LULUCF) of between 398-614 $MtCO_2e$ by 2030
BRAZIL	Reduce greenhouse gas emissions by 37% below 2005 levels in 2025

Source: information collated from each country's Intended Nationally Determined Contributions as communicated to the UNFCCC to the Parties (available at: https://www4.unfccc.int/sites/submissions/indc/Submission%20Pages/submissions.aspx).

229 Ibid.

2.2 The cost of green technology is rapidly falling

A green recovery from Covid-19 is also likely to be the right financial decision. Renewable energy technologies are already cheaper than fossil fuels in some locations. Energy generation from fossil fuels has historically been cheaper than renewable technologies, which had hampered progress towards a clean energy system.

An under-appreciated fact about energy technologies is that their costs improve year on year consistently, but at rates that vary widely between technologies. Over the last century, the inflation-adjusted costs of coal, oil and natural gas have not changed by more than an order of magnitude.[230] In contrast, the cost of solar photovoltaics has consistently dropped by around 10 per cent per year on average for the last four decades.[231] With wind and battery technologies also experiencing dramatic cost reductions in recent years, renewable energy is now the cheapest form of electricity generation in numerous places around the world.[232] In emerging market economies, the same trend has been observed. As shown in Fig. 9 (a) the weighted average cost of onshore wind in Brazil, India and China has fallen by around 60-80 per cent within the last two decades. Similarly, as Fig. 9 (b) demonstrates, solar PV has experienced cost reductions of around 70 per cent in the last decade alone in India and China.

These sharp reductions in costs have led to the adoption of renewables at an increasing rate. In the coming decade, wind and solar could each represent around 20 per cent of global electricity production (see Fig. 12). Some power grids will need increases in energy storage and demand flexibility if intermittent renewables are to become a larger proportion of power output. But there is a positive feedback associated with green-energy technologies. For example, as solar PV has higher uptake, the demand for batteries is likely to increase, which in turn is likely to accelerate the solar PV adoption.

One problem with the widescale adoption of renewable energy is intermittency. Solar power is only generated when the sun is shining, and wind power is only generated when it is windy. Too little sunshine and wind can risk blackouts, while too much of either must be stored and spilled (or wasted) to avoid supplying more electricity than the

230 Farmer, J. D., et al. “Sensitive intervention points in the post-carbon transition.” Science 364.6436 (2019): 132-134.
231 Farmer and Lafond (2016), Farmer, J. D., & Lafond, F. (2016). How predictable is technological progress? Research Policy, 45(3), 647-665.
232 International Renewable Energy Agency (IRENA) (2017). Rethinking energy 2017: accelerating the global energy transformation.

grid can handle. Renewables, therefore, typically need to be complemented by a combination of storage, demand-side responses, access to larger networks and complementary energy sources that can rapidly make up any shortfalls in supply, not least those caused by seasonal variations in weather.

FIG.9

DECLINING COSTS OF RENEWABLE ENERGY IN EMERGING MARKETS

FIG.9A

Onshore Wind Power in India, China and Brazil.

ONSHORE WIND POWER COSTS, WEIGHTED AVERAGE LEVELISED, 2018 USD PER MWH

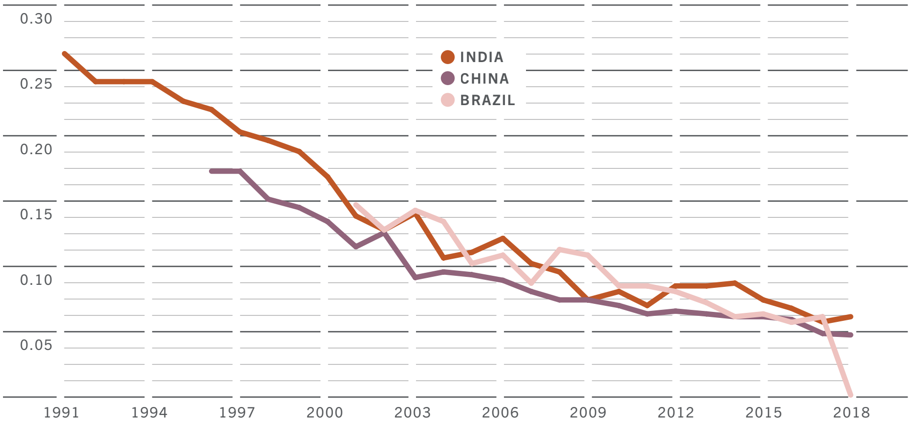
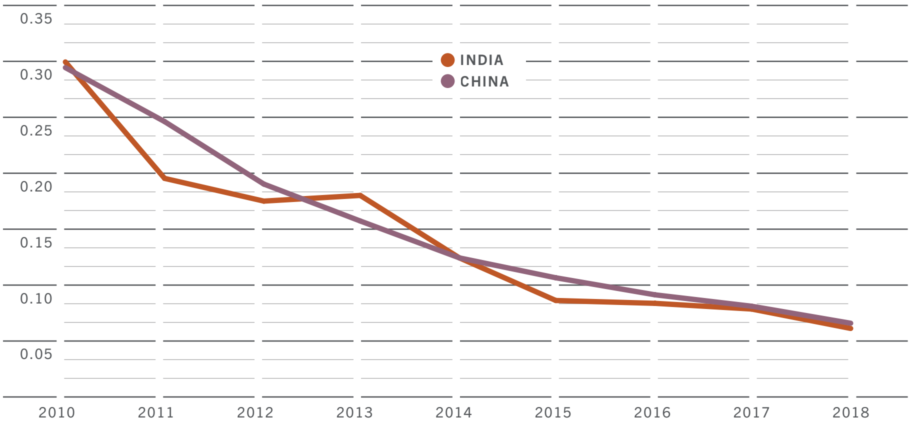


FIG.9B

Solar PV in China and Brazil

SOLAR PHOTOVOLTAIC COSTS, WEIGHTED AVERAGE LEVELISED, 2018 USD PER MWH

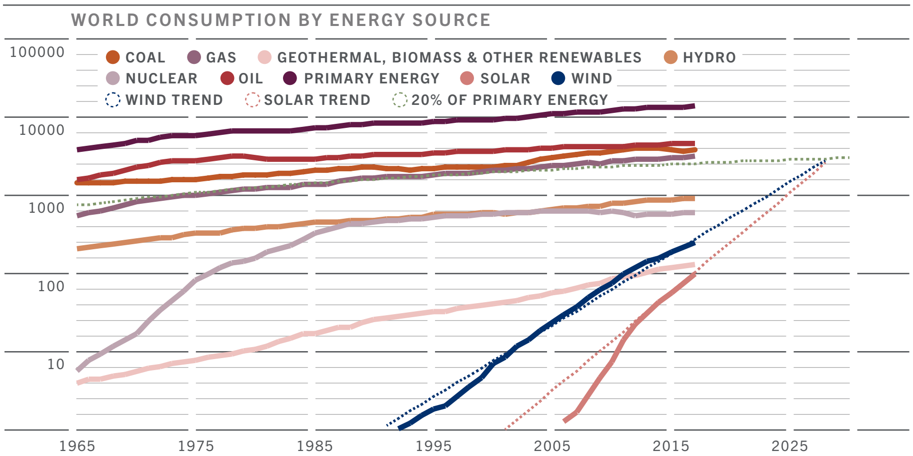


Source: Data and statistics Portal, IRENA (2020)

Fortunately, a range of possible energy storage solutions already exists, some of which are rapidly improving. The majority of installed storage capacity takes the form of pumped hydro storage systems, which pump water uphill when there is excess grid power and release water downhill to power turbines when more energy is needed. Their advantage is that it is a tried and tested approach that is already widely used around the world. However, they require hilly terrain. The cost of Lithium-ion (Li-ion) batteries has fallen dramatically in recent years,[233] with battery packs achieving cost reductions of around 21 per cent per annum since 2010. While Li-ion batteries have smaller storage capacity relative to other storage systems, they can be installed almost anywhere. Their use in the growing electric vehicle market is also likely to spur further improvements and cost reductions. While Li-ion batteries are currently the dominant battery technology, the growth in applications for storage technologies is expected to create new opportunities for other battery chemistries (such as solid-state batteries), to compete with Li-Ion.

FIG.10

Dotted lines follow the trajectory of the solar and wind trends to 20 per cent of primary energy. Note the vertical axis is logarithmic.



Source: BP Statistical Review of World Energy, 2018, 67th edition, all data 1965-2017

233 Cole, W. J., & Frazier, A. (2019). Cost projections for utility-scale battery storage (No. NREL/TP-6A20-73222). National Renewable Energy Lab. (NREL), Golden, CO (United States).

Hydrogen produced with electrolysis powered by renewable energy is a promising technological possibility that is attracting growing political support and business momentum. Hydrogen can be produced by passing an electric current through water and decomposing it into oxygen and hydrogen gas. When electricity made from renewable sources is used, the resulting "green hydrogen" becomes a source of storage for renewable electricity. Electrolysers could help integrate much larger amounts of intermittent renewable energy into the energy system. While producing hydrogen from renewable energy is currently more expensive than conventional sources, electrolyser costs are predicted to halve over the next few decades.[234] As renewable energy costs continue to fall, green hydrogen is predicted to reach cost parity in Australia, Germany and Japan by 2030.[235]

Green hydrogen also provides important opportunities for sectors that have been traditionally difficult to decarbonise through electrification. For example, many industries such as oil refining and ammonia production currently depend on natural gas. Switching to green hydrogen could significantly reduce the emissions intensity associated with these production processes. Green hydrogen can also be blended into natural gas pipeline networks (e.g. up to 20 per cent volume blends) to reduce emissions associated with heating and cooking in buildings or deliver hydrogen to markets without having to create new pipeline infrastructure.[236]

While ammonia is widely used in manufacturing agricultural fertilisers, producing green ammonia could provide further advantages for accelerating the green transition. Unlike hydrogen, which is difficult and costly to store in bulk, ammonia can be relatively easily converted to a liquid. Hence, "green ammonia", which is produced from green hydrogen, can be a useful chemical store of renewable energy. An existing supply chain and distribution network also already exists, which could readily facilitate global transportation. Moreover, as ammonia can also be used in a fuel cell or burnt in an engine, it could substitute for oil and play an important role in decarbonising the maritime industry.[237]

234 IRENA 2018, Hydrogen from renewable power: technology outlook for the energy transition.
235 Wood Mackenzie, 2019, Green hydrogen production: Landscapes, projects and costs.
236 Melaina, M. W., Antonia, O., & Penev, M. (2013). Blending hydrogen into natural gas pipeline networks. a review of key issues (No. NREL/TP-5600-51995). National Renewable Energy Laboratory.
237 Royal Society 2020, Ammonia: zero-carbon fertiliser, fuel and energy store. Policy Briefing.

Growing demand for green technologies and cleaner production processes offers important opportunities for emerging markets. For example, Brazil is the second largest producer of iron ore, but also has some of the lowest-cost renewable power in the world, with wind projects currently providing energy at USD23 per megawatt-hour. This compares with leading projects in the US (USD26 per megawatt-hour), India (USD29 per megawatt-hour) and Spain (USD29 per megawatt-hour).[238] Rather than exporting iron ore, Brazil could instead further process the mineral into direct-reduced iron (DRI) in a renewable-powered electric furnace. DRI can be exported to be further processed into steel. Not only does this significantly reduce emissions, it also increases the value-added for Brazil and reduces transported weight by around one third. Given their favourable conditions for variable renewable energy, Chile and Argentina also have the potential to become significant players in the growing market for green ammonia.[239] These countries are doubling their efforts to realise their potential, with Enaex (Latin America's leading suppliers of ammonium nitrate and explosives) recently announcing a strategic partnership with global energy services group ENGIE to develop a pilot plant in northern Chile.[240] China is also ramping up efforts in hydrogen and fuel cell development and envisions that hydrogen will represent 10 per cent of the Chinese energy system by 2040. In the first seven months of 2019, China increased its installed capacity of hydrogen fuel cells sixfold.[241] It is also shaping Wuhan, the capital of Hubei, to be a hydrogen city with around 5000 fuel cell vehicles and up to 100 fuelling stations by 2025.[242] Falling battery costs are also contributing to rapid uptake for smaller (two- and three-wheeled) electric vehicles in emerging economies. The Asia Pacific region in particular is set to dominate the growing battery market, with rapidly urbanising countries such as China and India expected to attract significant investment in battery companies over the coming years.[243]

238 Renewable Energy World (2020) "BNEF says solar and wind are now cheapest sources of new energy generation for majority of planet". Available at: https://www.renewableenergyworld.com/2020/04/28/bnef-says-solar-and-wind-are-now-cheapest-sources-of-new-energy-generation-for-majority-of-planet/

239 Armijo, J., & Philibert, C. (2020). Flexible production of green hydrogen and ammonia from variable solar and wind energy: Case study of Chile and Argentina. International Journal of Hydrogen Energy, 45(3), 1541-1558.

240 ENAEX (2019) ENAEX & ENGIE: On the path to a smooth zero carbon transition in the Chilean Mining Sector (available at: https://www.enaex.com/en/enaex-engie-on-the-path-to-a-smooth-zero-carbon-transition-in-the-chilean-mining-sector/)

241 Cleantech Group (2019) Hydrogen in China (Available at: https://www.cleantech.com/hydrogen-in-china/)

242 Green Tech Media (2019) 10 Countries Moving Toward a Green Hydrogen Economy (https://www.greentechmedia.com/articles/read/10-countries-moving-towards-a-green-hydrogen-economy).

243 Report Linker (2019) The market for the battery is expected to grow approximately at a CAGR of 12.31% during the forecast period of 2019. (Available at : https://www.globenewswire.com/news-release/2020/02/20/1988338/0/en/The-market-for-the-battery-is-expected-to-grow-approximately-at-a-CAGR-of-12-31-during-the-forecast-period-of-2019.html).

Decentralised energy systems based on distributed renewables also give emerging market economies new ways to provide energy access for all. This presents important opportunities for emerging markets. Traditionally, providing energy access to all involved costly investment in centralised energy infrastructure, with consequent adverse climate impacts associated with fossil fuel use. However, more decentralised energy systems involving distributed renewable energy technologies and micro-grids could allow emerging countries to leapfrog the centralised, emissions-intensive energy systems that characterise today's most developed countries.[244,245] Thanks to their declining cost and increasing flexibility, decentralised solar technologies are bringing power to more rural and remote communities in countries such as India[246] and Brazil[247] or China.[248] To date, such programmes have experienced varied degrees of success. Key challenges currently exist around coordinating the main stakeholders, selecting appropriate technologies and setting standards, regulations and tariff structures for these new energy systems.[249,250] However, we think such systems will help improve energy access and living standards across the world.

244 Alstone, P., D. Gershenson and D.M. Kammen (2015), 'Decentralized energy systems for clean electricity access', Nature Climate Change, 5(4), 305–14.

245 Levin, T. and V.M. Thomas (2016), 'Can developing countries leapfrog the centralized electrification paradigm?', Energy for Sustainable Development, 31, 97–107.

246 Yadav, P., Davies, P. J., & Palit, D. (2019). Distributed solar photovoltaics landscape in Uttar Pradesh, India: Lessons for transition to decentralised rural electrification. Energy Strategy Reviews, 26, 100392.

247 Mazzone, A. (2019). Decentralised energy systems and sustainable livelihoods, what are the links? Evidence from two isolated villages of the Brazilian Amazon. Energy and Buildings, 186, 138-146.

248 https://www.worldbank.org/en/news/feature/2011/04/06/solar-systems-for-400000-rural-households-china

249 He, G., & Victor, D. G. (2017). Experiences and lessons from China's success in providing electricity for all. Resources, Conservation and Recycling, 122, 335-338.

250 Yadav, P., Davies, P. J., & Palit, D. (2019). Distributed solar photovoltaics landscape in Uttar Pradesh, India: Lessons for transition to decentralised rural electrification. Energy Strategy Reviews, 26, 100392.

2.3 Key sectors that are the focus of a green recovery in emerging markets

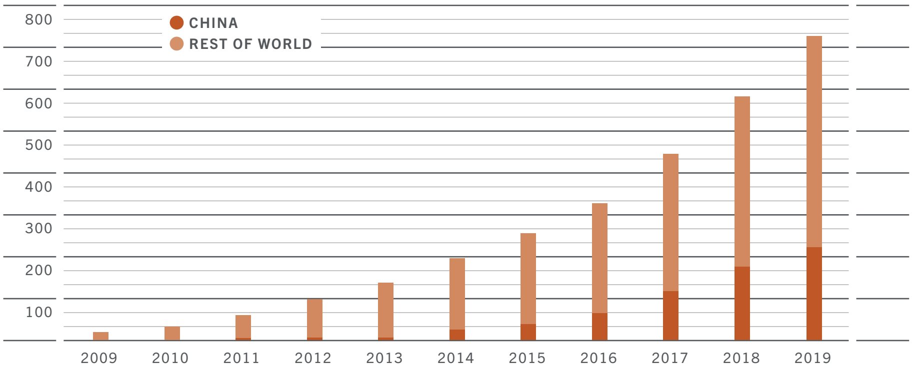
Emerging economies have already taken or planned large-scale action to tackle climate change. Here, we present the long-term industrial strategies of three countries – China, India and Brazil – to accelerate their transition towards a low-carbon economy. They are likely to strongly influence government investment post Covid-19 and could be used as an essential tool for a green recovery from the pandemic.

2.3.1. China

China now has the world's largest renewable energy capacity, with more than 184 gigawatts wind and 175 gigawatts solar installed. In 2018, the newly installed capacity of solar and wind energy in China was almost the same as that of the rest of world combined.[251] China supports the deployment of renewable energy through feed-in tariff policies, which started in 2009 for wind and in 2011 for solar. However, even though the installed renewable capacity is large in China, the country has equally large energy needs: only 5 per cent of the country's electricity was generated from wind and only 3 per cent from solar in 2019.[252] China aims to increase the share of non-fossil energy in total primary energy consumption to 20 per cent by 2030.[253]

FIG.11

CHINA'S AND THE REST OF THE WORLD'S SOLAR PV INSTALLED CAPACITY* (TERAWATT-HOURS)



* Based on gross generation and not accounting for cross-border electricity supply.

Source: BP Statistical Review of World Energy 2020

251 IRENA (2019). Renewable Capacity Statistics 2019.
252 China Energy Portal (2018). 2018 Electricity & Other Energy Statistics.
253 China NDRC (2016), China 13th Renewable Energy Development Five-Year Plan (2016-2020).

Greater adoption of renewable energy will bring economic benefits too, because China is the leader in solar panel manufacturing. In 2017, about two-thirds of the world's solar modules were produced in China.[254] China's solar manufacturing industry took off in the mid-2000s thanks to demand in overseas markets, especially in the European Union and the US. China's share in global solar manufacturing grew from about 1 per cent in 2001 to more than 50 per cent in 2010.[255] In the early 2010s, China shifted its solar strategy from exports to its domestic market because Chinese solar manufacturers were heavily hit by anti-dumping measures taken in the EU and the US. During this period, China implemented feed-in-tariffs and other policy subsidies to expand the domestic industry. Today, exports are once again becoming the main driving force of China's solar industry, with a diversification of export destinations to emerging markets, including South America, the Middle East and north Africa.[256]

Despite a temporary post-pandemic rise in coal usage, China intends to cut consumption of dirty fuel in the long term. China is the world's biggest consumer of coal, with 3.9 billion tonnes of coal consumed in 2018, and 70 per cent of the electricity produced in the country relying on coal. However, China has been developing clean coal technologies, with about 71 per cent of coal-fired power plants using the highly-efficient and lless polluting ultra-supercritical technology.[257] Furthermore, between 2016 and 2018, China phased out 8.1 billion tonnes of annual coal production capacity. Specifically, 20 gigawatts of low-efficiency and low-environmental-standard coal-fired power plants were closed.[258]

Energy-intensive industries are also covered by the Chinese strategy to reduce its reliance on fossil fuels. Above all, the Chinese government has been pushing to reduce excess industrial capacity in high-polluting and carbon-intensive industries within its wider effort of Supply-Side Structural Reforms launched in 2015. Government data shows that China has successfully cut down 150 million tonnes of crude steel production from 2016 to 2018.[259] China has achieved its overcapacity reduction goal in its

254 David Sandalow (2019). Guide to Chinese Climate Policy 2019.

255 Zhang, S., Andrews-Speed, P., Zhao, X., & He, Y. (2013). Interactions between renewable energy policy and renewable energy industrial policy: A critical analysis of China's policy approach to renewable energies. Energy Policy, 62, 342-353.

256 Liu, Y. (2019). Chinese Solar Manufacturers Increased Production, Export in 2018 While Domestic Installations Fell-Renewable Energy World.

257 XinhuaNet (2018). China has built the world's largest clean coal power supply system (in Chinese, 我国已建成全球最大清洁煤电供应体系).

258 China's Ministry of Ecology and Environment (2019). China's Policies and Actions for Addressing Climate Change 2019 (in Chinese, 中国应对气候变化的政策与行动2019 年度报告).

259 China's Ministry of Ecology and Environment (2019). China's Policies and Actions for Addressing Climate Change 2019 (in Chinese, 中国应对气候变化的政策与行动2019 年度报告).

13th Five-Year Plan (2016-2020), two years ahead of schedule. China also aims to cut overcapacity in cement, glass, and aluminium. Meanwhile, there are currently eight pilot regional carbon emission trading markets in operation in China, covering approximately 3,000 entities.[260]

China is also greening its transport sector. In 2009, the Chinese government initiated the "Ten Cities, Thousand Vehicles" programme to encourage the public purchase of electric vehicles (EVs). Generous subsidies provided to car manufacturers, local government procurement of EVs, and economic incentives to consumers have significantly boosted EV sales in China. In 2018, almost 45 per cent of the electric cars in the world were running on Chinese roads.[261] In 2019, the New Energy Vehicle policy mandated that EVs should account for at least 10 per cent of the cars produced and shipped by Chinese manufacturers and importers.[262] According to a recent report by iCET, China could be capable of phasing out petrol and diesel vehicles by 2040.[263]

2.3.2. India

India's primary energy consumption is expected to increase by 156 per cent by 2040, making it one of the largest sources of energy demand growth in the world.[264] Current trajectories expect that coal will meet the majority of the increase in demand.[265] However, air pollution is becoming a pressing issue in India. Living in some of the world's most noxious cities, Indian citizens are aware of the role of dirty coal in increasing respiratory illnesses and consequently, medical bills. With the Supreme Court declaring a public health emergency in 2019, the country is keen to adopt cleaner production methods, not only across energy but also agriculture and transport. Therefore, India has significant scope for pushing forward a green industrial strategy post-Covid 19. Key green growth opportunities include wind energy, solar power and increased energy efficiency.

India has one of the largest renewable energy capacity expansion programmes in the world.[266] India has a target of 175 gigawatts of installed renewable energy capacity by 2022, a fivefold increase from present levels.[267] By 2030 the country wants renewable energy to generate 40 per cent of total energy compared with today's 9 per cent.

260 International Carbon Action Partnership (2017). Emissions Trading Worldwide.
261 IEA (2019). Global EV Outlook 2019.
262 International Council On Clean Transportation (2018). China's New Energy Vehicle Mandate Policy.
263 Innovation Centre for Energy and Transportation (2019). A Study On China's Timetable For Phasing Out Traditional ICE Vehicles.
264 BP Energy Outlook (2019)
265 Ibid.
266 India's Nationally Determined Contribution
267 Ibid.

Studies show that it is technically feasible to have this level of renewable energy in India's grid with minimal curtailment.[268] The government's National Smart Grid mission is also working towards smarter integration of renewable energy. These ambitious renewable energy targets and the associated budgetary allocations show that the growth of the renewable energy sector is baked into India's development trajectory.

India is the fifth largest producer of wind power in the world, with ample potential to further scale up production and diversify into the offshore market. Wind power is the predominant contributor to renewable energy growth in India, accounting for 65 per cent of renewable energy installed capacity.[269] With over 7,600 kilometres of coastline, India's offshore wind potential is significant. Assessment studies suggest that the coastlines of Tamil Nadu and Gujarat have a potential for offshore wind farms of up to 100 gigawatt each.[270] The National Offshore Wind Policy is promoting offshore wind development in these areas, and local governments have committed to renewable purchase obligations. Tamil Nadu, which has more installed wind energy than leaders such as Denmark and Sweden, is poised to double its capacity by 2027.[271]

Solar energy is rapidly undercutting coal and delivering upon multiple development objectives. According to 2019 data, India is the cheapest producer of solar in the world.[272] Plummeting solar prices are threatening generation from conventional sources such as coal. Moreover, the off-grid and rooftop solar PV present a unique opportunity for households to reduce their bills, which is a priority for Indian energy users. The Indian market for solar lanterns and solar home systems is expected to grow to a total value of USD327 million by 2023.[273] The central government also has ambitious support schemes for solar energy. For example, the National Solar Mission includes the establishment of 25 large-scale solar parks, which will help reach the 100-gigawatt solar target by 2022. Highly competitive solar energy auctions also reveal a market appetite for increased growth in the sector. The government's renewable energy certificate scheme should also promote investment in the sector.

268 Palchak, David, et al. (2017). "GREENING THE GRID: Pathways to Integrate 175 Gigawatts of Renewable Energy into India's Electric Grid, Vol. I—National Study." NREL.

269 India's Nationally Determined Contribution

270 Singh and Koshy (2018). "Powerful winds of change: How India can benefit from offshore". DownToEarth.org

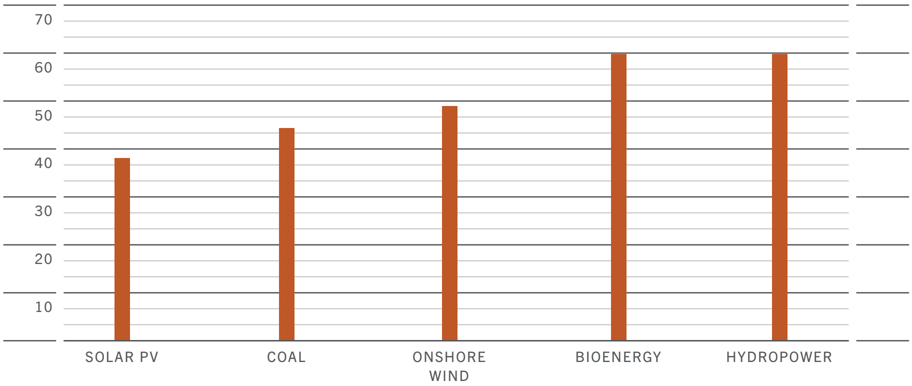
271 McKenna (2018). "This Indian state produces more wind power than Sweden or Denmark. World Economic Forum.

272 IRENA (2018) Renewable Power Generation Costs in 2018. Wood Mackenzie (2019) "India is now producing the world's cheapest solar power". World Economic Forum.

273 cKinetics (2019). "Peering into the future. India and the solar standalone products market". GOGLA

FIG.12

COST OF ELECTRICITY BY GENERATION TYPE IN INDIA
WEIGHTED AVERAGE LEVELISED COST, USD PER MWH



Source: IRENA (2018) for bioenergy and hydropower.
Wood Mackenzie (2019) for solar PV, coal and wind.

Finally, the market for energy efficiency is being boosted through favourable incentives for investors. Through National Missions for Enhanced Energy Efficiency, investors are partially covered for risks involved when lending to energy efficiency projects. Standards for energy efficiency are also tightening. And there is a tradable permit scheme for energy efficiency (Perform, Achieve and Trade) to encourage industries to deploy more energy efficient methods.

Some risks to the growth of green sectors in India include the poor health of state utilities, which are the main buyers of renewable energy. In some states, the poor financial health of utilities undermines their ability to purchase renewable energy. However, the government is aware of the issue and is therefore likely to take steps to address it.

2.3.3 Brazil

Following the Paris Agreement, Brazil has committed to a 37 per cent reduction in emissions by 2025 compared with 2005[274,275] and later announced an indicative target for a 43 per cent reduction by 2030.

The Federal Government expects to allocate around USD2 billion in investment for Brazil's economy to meet its NDC. The government's priority is energy efficiency, for example by encouraging the purchase of modern industrial equipment. Within the next ten years, Brazil expects to reduce its final annual energy consumption by 21 million tonnes of oil equivalent (8 per cent of 2018 consumption) thanks to increases in energy efficiency, mostly shared between industry (47 per cent of the efficiency gains) and transport (41 per cent).[276]

274 Brazil's Nationally Determined Contribution.
275 Ministério do Meio Ambiente (n.d.). Plano Nacional de Adaptação. Retrieved 20 March 2020, from https://www.mma.gov.br/clima/adaptacao/plano-nacional-de-adaptacao
276 Brasil, Ministério de Minas e Energia, Empresa de Pesquisa Energética (2020). Plano Decenal de Expansão de Energia 2029 / Ministério de Minas e Energia. Empresa de Pesquisa Energética. Brasília: MME/EPE.

Brazil aims to increase the proportion of renewables in its energy mix to 48 per cent by 2029 from 42 per cent today.[277] Brazil aims to increase solar electricity production fivefold, with micro- and mini-distributed solar generation to increase by a factor of 12. The government also wants to increase electricity production from wind turbines by 160 per cent within 10 years and increase hydropower production from large dams by 6.5 per cent and by 43 per cent from small reservoirs.

Compared with other countries, the Brazilian renewable energy strategy relies heavily on bioenergy. Brazil's ethanol programme was launched in the 1970s to provide an alternative to soaring oil prices. Four decades of continual development resulted in a steady increase in production (see Fig. 13) and helped the country's share of renewables in the energy mix to be consistently above 40 per cent during the past decade.[278] The government launched a policy called Renoviabio to expand the national use of biofuels and prevent 95.5 million tonnes of CO_2 by 2029.[279,280] To implement the policy, the government created a financial instrument called Decarbonisation Credits (CBIOs) in 2019. A CBIO is a certificate that producers or importers of biofuels can issue through domestically regulated financial institutions.[281] Since 2020, fuel distributors have been legally bound to buy CBIOs to help offset the carbon emissions of their products.[282] While CBIOs should help further develop the biofuel industry, the policy has also been criticised because financial penalties for non-compliance are capped, which may make it cheaper for very large companies to ignore the law than to buy CBIOs.[283, 284]

277 Empresa de Pesquisa Energética - EPE (2019). Balanço Energético Nacional 2019: Ano base 2018. Brazilian Energy Balance 2019 Year 2018. Empresa de Pesquisa Energética - EPE - Rio de Janeiro.

278 Empresa de Pesquisa Energética - EPE (2019). Balanço Energético Nacional 2019: Ano base 2018. Brazilian Energy Balance 2019 Year 2018. Empresa de Pesquisa Energética - EPE - Rio de Janeiro.

279 Conselho Nacional de Política Energética – CNPE (24 June 2019). Resolution N. 15.

280 Agência Nacional do Petróleo, Gas Natural e Biocombustíveis (n.d.). RenovaBio. Retrieved 20 March 2020, from http://www.anp.gov.br/producao-de-biocombustiveis/renovabio

281 Casa Civil da Presidência da República. Imprensa Nacional (21 November 2019). Ordinance N. 419 of November 20th, 2019. Retrieved 5 March 2020, from http://www.in.gov.br/web/dou/-/portaria-n-419-de-20-de-novembro-de-2019-228863910

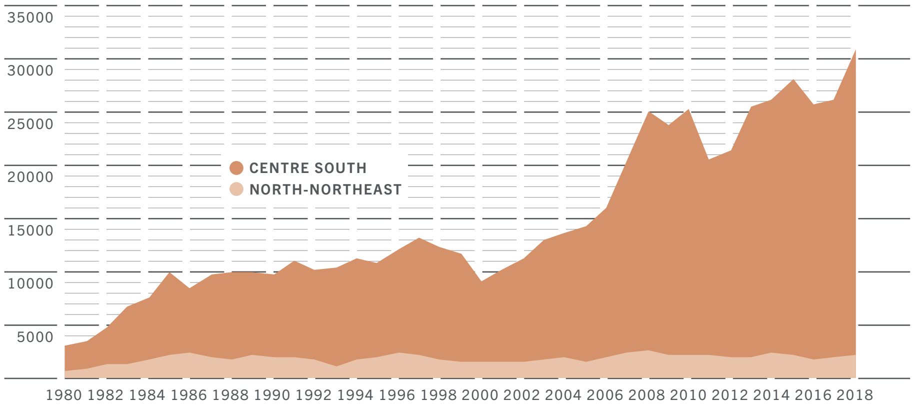
282 Ministério de Minas e Energia (21 November 2019). MME avança na sustentabilidade e regulamenta o Crédito de Descabornização – CBIO. Retrieved 5 March 2020, from http://www.mme.gov.br/web/guest/todas-as-noticias/-/asset_publisher/pdAS9IcdBICN/content/mme-avanca-na-sustentabilidade-e-regulamenta-o-credito-de-descarbonizacao-cb-2

283 Secretaria de Petróleo, Gás Natural e Biocombustíveis (n.d.). Perguntas e Respostas. Retrieved 20 March 2020, from http://www.mme.gov.br/web/guest/secretarias/petroleo-gas-natural-e-biocombustiveis/acoes-e-programas/programas/renovabio/documentos/perguntas-e-respostas

284 NovaCana (10 May 2018). Regras do RenovaBio provocam disparidade e beneficiam grandes distribuidoras. Retrieved March 18, 2020, from https://www.novacana.com/n/etanol/distribuidora/quanto-custar-1-cbio-regras-disparidade-beneficiam-grandes-distribuidoras-280318

FIG.13

EVOLUTION OF ETHANOL PRODUCTION IN BRAZIL, MILLION CUBIC METRES



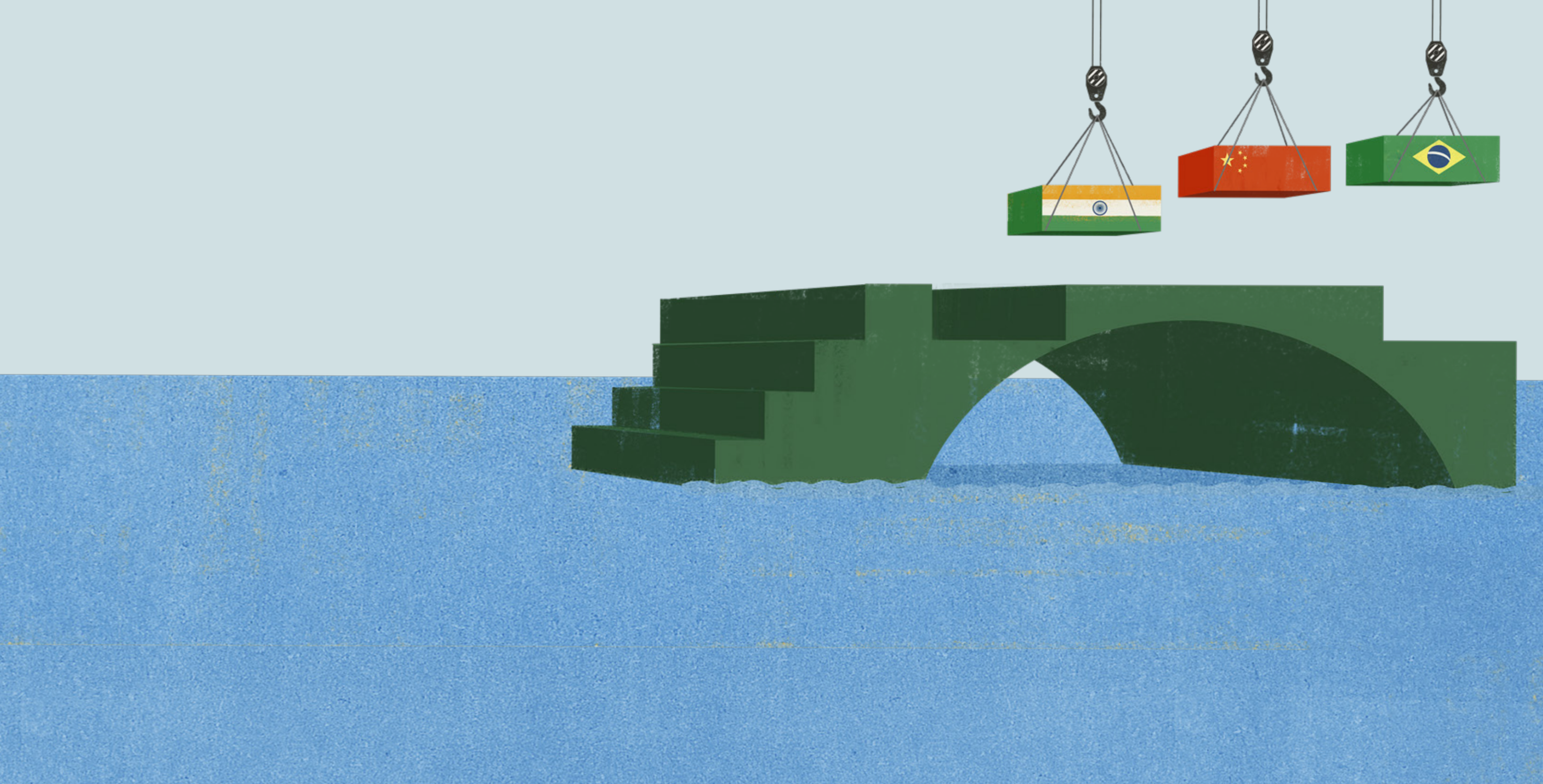
Source: UNICA (2020). Histórico de produção e moagem

A key sector for Brazil in terms of climate change responsibility is land use. The aggregate land use-related emissions between 1990 and 2018 accounted for 80 per cent of all Brazilian emissions.[285] Reducing deforestation and encouraging reforestation would also constitute an immense opportunity for climate change mitigation. From 2005 to 2010, overall national emissions fell 34 per cent thanks to land-use measures, at a time when all sectors but forestry increased their emissions.[286] However, ongoing policies are not exploiting this potential. Inaction in the past couple of years has led to a strong increase in the deforestation rate, by 63 per cent in 2019 compared with 2018.[287]

285 Observatório do Clima (2019). Análise das Emissões Brasileiras de Gases de Efeito Estufa e suas Implicações para as Metas do Brasil: 1970-2018
286 SEEG Brasil (n.d.). Emissões Totais. Retrieved 3 March 2020, from http://plataforma.seeg.eco.br/total_emission#
287 Imazon (2019, August). Boletim do Desmatamento da Amazônia Legal. Retrieved 29 February 2020, from https://imazon.org.br/publicacoes/boletim-do-desmatamento-da-amazonia-agosto-2019/

Section III

The role of finance in the green recovery



The role of finance in the green recovery

The Covid-19 pandemic has triggered huge upheaval across finance and industry. But one potential positive is the opportunity to create a more sustainable world by sensibly deploying vast government stimulus packages.

Governments have a large arsenal of low-carbon support policies available that are labour intensive with relatively high economic multipliers. These include targeted grants, investment tax credits, currency hedging instruments, feed-in-tariffs and renewable energy auctions.[288] Together, governments and international financial institutions can help manage sovereign risk, currency risk, asymmetric information on creditworthiness and other bottlenecks to clean energy investment in emerging markets. Private-sector investors, for their part, can take action to minimise their exposure to assets that are subject to the physical and transition risks of climate change, such as the decline in oil prices. They can engage directly with governments, working together to boost green investments in emerging markets.

The financial sector, with its expertise in structuring products, establishing investment vehicles and coming up with innovative solutions, can help propel the green recovery.

This section first presents the current state of climate finance (section 3.1), focusing on mitigation (subsection 3.1.1) and adaptation (subsection 3.1.2). We then mention opportunities and challenges for the uptake of climate finance (section 3.2). We finally look at three levers for change (section 3.3): the private sector re-evaluation of portfolio risks (subsection 3.2.1), the role that governments can play in phasing out fossil fuel subsidies and fostering green investment (subsection 3.2.2) and the role that central banks can play in the transition towards a low-carbon economy (subsection 3.2.3).

288 Hepburn, C., O'Callaghan, B., Stern, N., Stiglitz, J., & Zenghelis, D. (2020). Will Covid-19 fiscal recovery packages accelerate or retard progress on climate change?. Oxford Review of Economic Policy, 36.

3.1 The current state of climate finance

3.1.1 Financing climate change mitigation

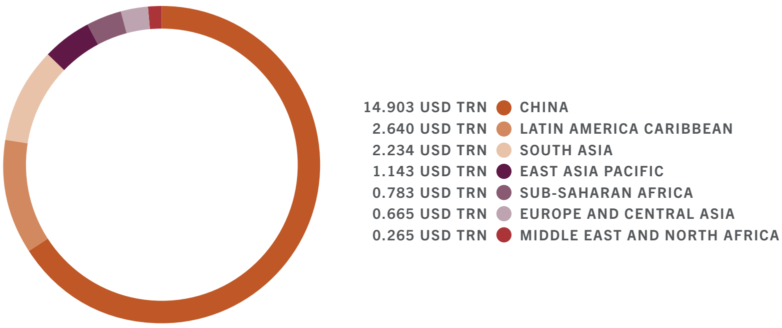
Before the coronavirus pandemic, the green economy already represented a substantial share of world GDP. According to FTSE Russell, the global green economy – which includes clean energy, energy efficiency, water, waste and pollution services – now accounts for as much of the global stock market as the fossil fuel sector (6 per cent) and is asserted to offer more significant and safe future investment opportunities.[289]

Many sectors, from energy and industry to agriculture, transport and forestry require low-carbon financing. While the power sector receives the majority of low-carbon funds (USD337 billion in 2017/2018)[290], it needs a sixfold increase in investment by 2050 (relative to 2015) to limit warming to 1.5°C.[291] Sectors such as cement, aluminium, iron and steel need to undergo radical transformations to meet the net-zero target. Private-sector involvement will help make such investments a reality.

In emerging economies, the opportunities to invest in climate-smart assets will be very large. The International Finance Corporation, a member of the World Bank Group, estimates that climate-start investments in emerging markets will be in the range of USD22.6 trillion between 2016 and 2030, 65 per cent of which could be located in China.[292]

FIG.14

CLIMATE-SMART INVESTMENT POTENTIAL, 2016-30, USD TRN, TOTAL: USD22.633 TRN



Source: Climate Finance Leadership Initiative (2019). "Financing the Low Carbon Future: A Private-Sector View on Mobilizing Climate Finance"

289 UNFCCC (2018). "Green Economy Overtaking Fossil Fuel Industry - FTSE Russell Report".
290 CPI (2019). Global Landscape of Climate Finance 2019 [Barbara Buchner, Alex Clark, Angela Falconer, Rob Macquarie, Chavi Meattle, Rowena Tolentino, Cooper Wetherbee]. Climate Policy Initiative, London.
291 IPCC, "Special Report: Global Warming of 1.5 degrees Celsius: Summary for Policymakers," Geneva 2018.
292 International Finance Corporation (2016). Climate Investment

Climate finance has to support the growth of low-carbon sectors and the transformation of polluting sectors. The Climate Finance Leadership Initiative, led by Michael Bloomberg, was created to mobilise private capital at the global level. In its report at the end of 2019, it highlighted two pillars for financing an effective transformation: [293]

1. ***Increasing low-carbon investment:*** tried and tested technologies such as solar panels, wind turbines, batteries and smart grids should be deployed at scale to meet the goals of the Paris Agreement. This is an area where the private sector can play a clear leadership role and galvanise greater quantities of finance. It can work with governments to create more suitable investment conditions by, for example, negotiating power purchase agreements (PPAs).
2. ***Supporting the transition of carbon-intensive sectors:*** not all industries have zero carbon alternatives that are currently economically viable. Sectors such as iron, steel, cement and aluminium have no “off-the-shelf” commercially viable zero-carbon solutions yet. In these sectors, investments have to focus on fundamental research and innovation, as well as the diffusion of recently developed technologies.

There are signs that low-carbon finance will surge in the coming decade. Oil supermajor British Petroleum (BP) has announced its plan to become a net-zero emissions company by 2050.[294] JP Morgan declared that it will halt financing new oil and gas projects in the Arctic.[295] As an indication of the direction of the wind, Jeff Bezos, Amazon’s chief executive and the world’s richest man, committed USD10 billion to address the climate crisis in a new initiative he called the Bezos Earth Fund.[296] Such announcements are becoming increasingly frequent, signalling a shift towards going green. Markets will observe these shifts, take into account existing and future cost declines, and asset prices will move in advance of revenue streams.

Low-carbon finance has already grown exponentially over the past 10 years. One notable innovation is green bonds. These are taking off in emerging economies. For example, China launched its green bond markets in late 2015[297] and, since then, has quickly become a leader in green finance. In 2017, one third of the world’s green bonds were issued by China.[298]

293 Climate Finance Leadership Initiative (2019). “Financing the Low-Carbon Future: A Private-Sector View on Mobilizing Climate Finance”

294 BP (2020). “BP sets ambition for net zero by 2050, fundamentally changing organisation to deliver”. Press release.

295 DeMarban (2020). “JPMorgan Chase says it won’t back new Arctic oil and gas projects”. News article.

296 New York Times. (2020) “Jeff Bezos Climate Change Earth Fund”.

297 https://chinadialogue.net/en/business/9128-china-s-green-bond-market-booms-with-more-clarity-in-policy/

298 https://chinadialogue.net/en/business/10387-international-investors-eye-china-s-green-bonds/

The most common type of green bonds is a "use of proceeds bond", in which proceeds from the debt issue are earmarked for green projects but the debt is backed by the issuer's entire balance sheet.[299] Issuers in this category include the World Bank and the European Investment Bank. The advantage of this type of green bonds is that they have the same credit rating as any other debt belonging to the issuer, meaning that investors can swap non-green bonds for green ones without adding new risk. Other types of green bonds include those that are linked to specific green-energy projects, in which there is only recourse to the project's assets and balance sheet. The exponential growth of green bonds, despite their slightly higher transaction costs (due to the need to track the use of proceeds), can be attributed to their role in signalling that the issuer supports green projects and in attracting new investors that are environmentally conscious. Municipal-level energy efficiency bonds are another innovation. They are backed by the creditworthiness of the borrower, which in this case is a municipality, and are used to finance long-term energy efficiency improvements in cities, such as switching to LED street lighting.[300] The bond framework makes it easier to raise upfront capital and the savings from improved energy efficiency make it relatively easy to pay back the debt.

However, much work remains to be done in terms of galvanising private finance at scale for the low-carbon transition. The USD260 billion of green bonds still accounts for a tiny share of the global bond market (worth USD100 trillion).[301] Estimates of the total investment required to achieve a 1.5 °C scenario range from USD2 trillion to USD6 trillion annually between 2016 and 2050.[302] Institutional investors, such as pension funds, insurance companies and sovereign wealth funds, could provide some of the required capital. But intermediation at scale is currently hampered by the relative lack of standardised products that manage risk and facilitate investment. The variance in project size and type creates due diligence costs. There is a need for greater standardisation and packaging of green investments to make them more accessible to institutional investors.

299 "Explaining green bonds," Climate Bonds Initiative.

300 Chris Nelder "How green bonds could unleash the Kraken of energy transition," SmartPlanet. (24 November 2013).

301 Ibid.

302 CPI (2019). Global Landscape of Climate Finance 2019 [Barbara Buchner, Alex Clark, Angela Falconer, Rob Macquarie, Chavi Meattle, Rowena Tolentino, Cooper Wetherbee]. Climate Policy Initiative, London; New Climate Economy (2014). "Infrastructure Investment Needs of a Low-Carbon Scenario".

3.1.2. Financing climate adaptation

While common narratives around adaptation have often focused on the future, the reality is that adaptive investments are already needed today. Since pre-industrial times, global average temperatures have increased by 1°C; in many countries, temperature increases and the incidence of heatwaves have been far larger.[303] Without proper adaptation, the size and scale of economic and social losses is significant. Delaying mitigation and adaptation will only increase the damage – not least to asset prices.[304] As of 2015, the world's stock of manageable assets was estimated to be USD143 trillion.[305] The value at risk to 2100 due to climate change is expected to be USD4 trillion, which is roughly equivalent to the total value of all the world's listed oil and gas companies or Japan's entire GDP.[306] Acting today to curtail global warming and climate-proof our economies can thus save trillions of dollars in net present value terms.

Even simple adaptive efforts can go a long way. According to the Global Commission on Adaptation (GCA), "early warning systems save lives and assets worth at least ten times their cost. Just 24 hours' warning of a coming storm or heatwave can cut the ensuing damage by 30 per cent and spending USD800 million on such systems in developing countries would prevent USD3–16 billion per year in losses."[307] Moreover, adaptation is not a question of developed versus developing countries. The wildfires in Australia and California illustrate how even the most advanced economies are underprepared in the face of climatic extremes.

The need to adapt is all the more urgent as the risk of unmitigated climate change looms. Our pessimistic, 'worst-case' emissions scenario would lead to average summer temperatures in India, Brazil and South Africa being some 4°C above historical levels (1985-2005 average). For China, the forecast is for a 5°C warming; for Russia it is over 6°C.

303 ClimateAnalytics (2016). "Global warming reaches 1°C above preindustrial, warmest in more than 11,000 years".
304 Economist Intelligence Unit (2015). "The Cost of Inaction". Report.
305 Ibid.
306 Ibid.
307 Global Commission on Adaptation. (2018). Global Commission on Adaptation.

Adaptation to climate change will take many forms:

- ***Large infrastructure projects, such as dikes, would increase resilience at regional and systemic level.*** Capital-intensive flood risk investments need climate finance because of the large sums of money involved. However, such investments are public goods: everyone benefits from them and no one can appropriate rents. As such, these investments are often government-led but with ample room for private-sector involvement and financing.
- ***Small-scale investments in cooling that improve climate-resilience.*** Investments in cooling are modular, decentralised, small and dispersed. But when added together at a city level, the sums required can be large. For example, as heatwaves become more frequent, plants and firms will want to invest in cooling technologies that will protect their workers and vulnerable capital. Such solutions are extremely important for preserving labour productivity and will require innovative financial structures.
- ***Finally, risk transfer through insurance has long constituted a form of adaptation to natural catastrophes.*** Losses from natural disasters are trending upwards. According to Munich RE, the total losses from natural disasters have amounted to USD5 trillion since 1980, and 70 per cent of these losses were uninsured.[308] Further development of disaster insurance will be required to reduce the impact of climate change on livelihoods.

Climate finance is still mostly geared towards mitigation. Funds for large-scale adaptation are lacking. According to CPI, mitigation finance accounted for 93 per cent of total flows in 2017/2018 while adaptation finance made up only 5 per cent of flows.[309] Total adaptation financing is around USD23 billion per year, of which a very large share is located in emerging economies (USD11 billion in south-east Asia and Pacific, USD3 billion in Latin America and the Caribbean and USD3 billion in Africa). [310] The source of these adaptation funds is primarily national, bilateral and multilateral development finance institutions, government, and climate funds. The required level of global adaptation financing is almost eight times greater – estimated at USD180 billion annually for the period 2020-2030[311] and the USD50 billion per annum needed by the Non-Annex I countries to achieve their nationally determined contributions (NDCs).[312]

308 From: https://www.munichre.com/en/risks/natural-disasters-losses-are-trending-upwards.html. Last consulted on 24 March 2020.
309 CPI (2019b). Tracking Adaptation Finance Flows: A snapshot of global adaptation investment and tracking methods.
310 Ibid.
311 Global Commission on Adaptation (2019). “Adapt Now: A Global Call for Leadership on Climate Resilience. Global Commission on Adaptation.”
312 UNEP (2018). “The Adaptation Gap Report 2018.”

Currently, adaptation finance is distributed across water and wastewater management, agriculture and land use, and disaster risk management, which account for 32 per cent, 24 per cent and 22 per cent, respectively, of the USD23 billion worth of annual funds.[313]

The private sector is doing little to finance large-scale adaptation. Adaptation represents only 0.1 per cent of private climate finance flows, although this could be skewed downward by measurement issues.[314]

This lack of interest in adaptation may mean that private assets are improperly defended, while hugely profitable opportunities may be missed. In emerging economies, this lack of interest may be caused by many factors, such as the high cost of capital, the lack of access to capital for small and medium businesses, insufficient awareness about climate change and regulatory failures, such as the lack of property rights. Yet adaptation prevents major damages, makes resources more productive and reduces investor risk, which can also bring down the cost of capital. Overall, it is estimated that for every dollar invested in adaptation, the returns could be USD2-10.[315] The GCA estimates that investing USD1.8 trillion globally in early warning systems, climate-resilient infrastructure, improved dryland agriculture, global mangrove protection and making water resources more resilient between 2020 and 2030 could generate USD7.1 trillion in total net benefits.[316]

There is a clear market opportunity in large-scale adaptation finance. Firstly, national governments and cities could turn to financial institutions to fund large-scale, long-term projects. Secondly, the market for the provision of large-scale adaptation infrastructure will grow. Long-term contracts and public-private partnerships for the provision of adaptation infrastructure will emerge. Because the benefits of adaptation to the economy and livelihoods are immense, local and national public authorities will be willing to invest in it, even under high interest rates. According to Swiss RE, up to 65 per cent of future climate losses could be prevented using cost-effective adaptation measures.[317]

313 CPI (2019). Global Landscape of Climate Finance 2019 [Barbara Buchner, Alex Clark, Angela Falconer, Rob Macquarie, Chavi Meattle, Rowena Tolentino, Cooper Wetherbee]. Climate Policy Initiative, London.

314 Ibid.

315 World Resources Institute. (2019). “Estimating the Economic Benefits of Climate Adaptation Investments.” Technical Paper

316 Global Commission on Adaptation. (2018). Global Commission on Adaptation.

317 Swiss RE. (2014). Economics of Climate Adaptation – Shaping climate-resilient development. A global overview of case studies with a focus on infrastructure.

__However, there are several additional barriers to scaling up adaptation finance, when compared to mitigation finance.__ Adaptation investments tend to be cost-saving in nature which, for various behavioural reasons, may be less attractive than revenue-generating investments.[318] Furthermore, adaptation investment can incur high upfront costs.[319] The benefits from adaptation investments tend to accrue in the longer term, but many private sector actors also have high discount rates. This may be exacerbated if boards are pushing for short-term goals instead of looking at the long-term financial health of their companies.[320] Joint public-private ventures may provide a solution to some of these barriers. For example, a case study in Nu River Valley in south-western China showed public-private partnerships could enhance farmers' resilience to drought and increase their adaption capabilities.[321]

__In that regard, smaller-scale adaptation provides one main advantage: costs and benefits are private.__ Adaptation options can therefore be more easily assessed against their costs to private owners, using traditional risk assessment methods and cost-benefit analyses. The Economics of Climate Change Adaptation Working Group has developed a framework for climate change adaptation, asking five key questions to evaluate the suitability of potential projects:[322]

- Where and from what are we at risk?
- What is the magnitude of the expected loss?
- How could we respond?
- How do we execute?
- What are the outcomes and the lessons?

__Businesses are likely to significantly underestimate their exposure to climate change.__ Shocks are difficult to predict because they are likely to come from indirect channels. A review of 1,600 corporate adaptation strategies found that, while companies tend to assess the exposure of their supply chains, their assessments do not often account for the disruptions that climate change could have on consumption, and therefore on the demand for their products. While most of them planned some form of adaptation measures in the future, 18 per cent mentioned no specific adaptation approach to reduce their climate change exposure.[323]

318 UNEP, 2016a. The Adaptation Finance Gap Report 2016.

319 Climate Investment Fund (2016) "Private Sector Investment in Climate Adaptation in Developing Countries: Landscape. Lessons Learned and Future Opportunities".

320 Ibid.

321 Zhang, Liyun, et al. "Public-private partnership in enhancing farmers' adaptation to drought: Insights from the Lujiang Flatland in the Nu River (Upper Salween) valley, China." Land use policy 71 (2018): 138-145.

322 Economics of Climate Change Adaptation Working Group. (2009). Shaping Climate Resilient Development: a Framework for Decision-making.

323 Goldstein, A., Turner, W. R., Gladstone, J., & Hole, D. G. (2019). The private sector's climate change risk and adaptation blind spots. Nature Climate Change, 9(1), 18-25.

Insufficient adaptation calls for a stronger role on the part of the insurance sector in covering businesses against potential losses. There is a need for the development of specific insurance against the risks of climate change. A wide range of products may be developed, including:[324]

— Traditional risk-transfer products for natural disasters such as cyclones, storms, floods or forest fires;
— Alternative products against natural disasters, such as parametric insurance;
— Crop insurance against extreme weather;
— Micro-insurance products to address the needs of small farmers in low-income countries that cannot access traditional insurance;
— Services that support the issuance of catastrophe bonds

Furthermore, the insurers will have a strong role in shaping business adaptation. Because they have expertise in catastrophic risk modelling and risk pricing, they may be better placed to assess potential systemic costs. As soon as they start protecting businesses from climate change, insurers will want to make sure that all precautions against climate damages have been taken, and may thus become a strong driver of climate change adaptation. It is also worth noting that emerging markets have been driving the growth of the insurance sector, and projections indicate that 60 per cent of the insurance market will be in emerging economies in ten years' time.[325]

324 The Geneva Association (2018) Climate Change and the Insurance Industry: Taking Action as Risk Managers and Investors Perspectives from C-level executives in the insurance industry.
325 Swiss Re's Sigma (2019). Emerging Markets to Drive Global Insurance Growth over Next Decade. Insurance Journal. 8 March 2019.

3.2. Opportunities and challenges in unlocking more green financing

The Covid-19 pandemic has created a window of opportunity to finance long-term sustainable solutions. Governments around the world have already announced unprecedented stimulus packages, with sizeable sums directed towards green industries with high job potential and economic multipliers.[326]

To unlock more private finance, especially in emerging markets, several challenges must be addressed:

1. ***Private finance for the low carbon-transition is not always available where it needs to be.*** Renewable energy added over 2009-2019 has principally been installed in China, Europe and the United States (see Fig. 15). Except for China, emerging markets receive a small proportion of renewable energy investment. Most climate finance – 76 per cent of the tracked total – is still invested in the same country in which it is sourced, revealing a strong "domestic preference" among investors who understand local risks better.[327,328] The issue of unknown risks is exacerbated since many cities in emerging markets do not have a credit rating. This prevents large-scale private investment in mass transit, energy-efficient buildings and other projects to reduce emissions.[329] Addressing this issue is key since cities are responsible for more than 70 per cent of CO_2 emissions.

326 Hepburn, C., O'Callaghan, B., Stern, N., Stiglitz, J., & Zenghelis, D. (2020). Will Covid-19 fiscal recovery packages accelerate or retard progress on climate change?. Oxford Review of Economic Policy, 36.

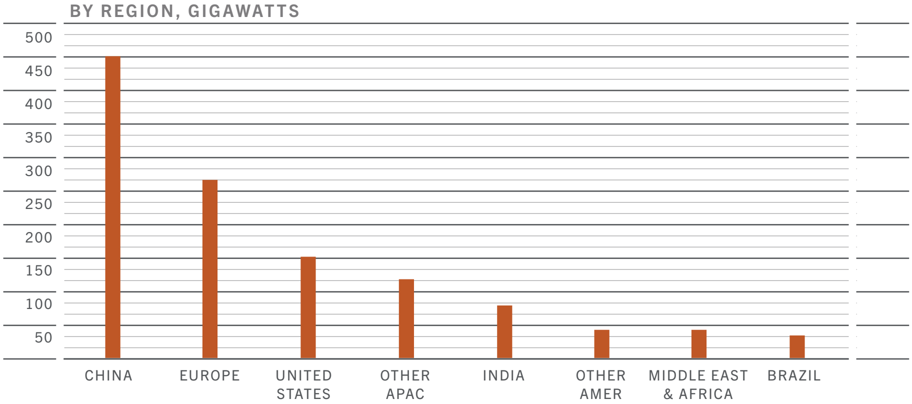
327 CPI (2019). Global Landscape of Climate Finance 2019 [Barbara Buchner, Alex Clark, Angela Falconer, Rob Macquarie, Chavi Meattle, Rowena Tolentino, Cooper Wetherbee]. Climate Policy Initiative, London.

328 Ibid.

329 Hoyer (2019). "Without private finance, there will be no green transition. Here is what needs to happen". World Economic Forum.

FIG.15

RENEWABLE ENERGY CAPACITY ADDED BETWEEN 2009 AND 2019 BY REGION, GIGAWATTS



Source: Frankfurt School-UNEP Centre/BNEF (2019). Global Trends in Renewable Energy Investment 2019. Focus Chapter.

2. ***Some sectors that are key for the green transition struggle to attract funds.*** Of the USD326 billion worth of private climate finance in 2017/2018, 85 per cent flowed to renewable energy, 14 per cent to low-carbon transport, and under 1 per cent to all other subsectors.[330] In the land-use sector, monitoring is difficult, making it hard to verify the emissions reduction achieved through certain investments – although, this is rapidly changing with the deployment of satellite technology. However, other reasons for the lack of finance could include less certain business models, and the fact that low-carbon innovation in industry and agriculture is relatively new.
3. ***There is a lack of diversity in terms of who is investing in the low-carbon economy, with scope to bring on board larger investors.*** Project developers and banks are still responsible for the majority of financial flows. According to Climate Finance Leadership Initiative, "asset managers and asset owners generally prefer to allocate larger sums per transaction than the typical clean energy investment opportunity allows. Over the last 10 years, the average new clean energy project investment has hovered around USD50 million. In comparison, a survey of pension funds and insurance companies suggests that a minimum asset finance deal size of USD100 million is probably required for direct investment." [331] To bring on board bigger investors, low-carbon projects need to be larger and more standardised. To address this, project developers and banks have used securitisation and bonds to aggregate clean

330 Hoyer (2019). "Without private finance, there will be no green transition. Here is what needs to happen". World Economic Forum.

331 Climate Finance Leadership Initiative (2019). "Financing the Low-Carbon Future: A Private-Sector View on Mobilizing Climate Finance".

energy investments into financial products, achieving a scale that enables larger investors to support smaller project sizes. For example, in 2013, Goldman Sachs structured the first rated securitisation of solar energy globally through its JRE Mega Solar Project Bond Trust.[332] Institutional investors could provide much of the capital if standardised products are created to minimise the need for bespoke (and hence costly) due diligence.

However, many opportunities are available and could lead to an even more dramatic surge in green finance:

1. ***Re-direction of government expenditure to green sectors.*** With vast sums being spent on stimulating the global economy during the pandemic, there is an opportunity to leverage this money to fund green industries with high economic multipliers. A challenge is that many emerging markets are instead using these funds to finance carbon-intensive sectors. More pressure needs to be put on national governments to re-orient this expenditure or attach green conditionalities to rescue packages for carbon-intensive sectors – something we are already seeing in developed markets. France's USD7.6 billion bailout of Air France, for example, is conditional on the company reducing emissions by 50 per cent by 2024 and meeting a minimum standard of 2 per cent renewable fuel.[333] Canada, meanwhile, is using relief directed at the energy sector to clean up unused oil well sites and upgrade methane monitoring and reduction technologies.[334] But for now such examples are relatively isolated and more needs to be done. Given that many of these stimulus packages are relatively recent, there is a window of opportunity to engage with governments on the best use of these funds, and this conversation must take into consideration the long-term risks that carbon-intensive assets face due to declining renewable energy and battery prices, new patterns of demand, political momentum for climate action and physical climate risks.

332 Ibid.
333 Vivid Economics and Finance for Biodiversity Initiative (2020) Green Stimulus Index.
334 Ibid.

2. ***Greater incentives for green investment.*** It is easy to continue with old investment habits. But that is becoming increasingly risky as climate damage intensifies, climate policy stringency increases (e.g. tariffs on carbon-intensive imports as suggested by French President Emmanuel Macron) and renewable costs decline.[335] In fact, the green transition may produce net savings. Contrary to conventional thinking, the latest evidence shows that the savings produced from switching to clean energy may outstrip the costs.[336]
3. ***Use of public-sector finance to attract more private-sector funds.*** Europe has made clear its ambition to use public finance to encourage private funds to support the growth of green sectors. Specifically, the European Investment Bank (EIB) has committed to spend USD1.1 trillion on low-carbon projects over the next decade.[337] This is particularly promising as multilateral institutions such as EIB "can play an important role by acting as first movers in opening up new emerging markets, establishing market-based transactions structures, and preparing the ground for commercial investment to follow".[338]
4. ***Shift of subsidies towards low-carbon transition.*** Only a small share of the money that currently goes towards subsidising fossil fuel production would be sufficient to fund the green-energy transition globally.[339] Almost everywhere, renewables are so close to being competitive that a 10-30 per cent subsidy swap would decisively tip the balance in favour of renewable energy.[340]
5. ***Huge potential of breakthrough innovations.*** Investing in breakthrough innovations is certainly risky but could earn high rewards. There are first-mover advantages in developing novel zero-carbon technologies in conventionally high emissions sectors. Projects such as Sweden's HYBRIT steel project are trying to produce zero-carbon steel by using hydrogen instead of coking coal.[341] If an economically viable solution is developed, it could produce a highly valuable patent that disrupts the existing market paradigm. A similar story may play out in agriculture: lab-grown meat is a risky venture but if it can prove to be cost-competitive against animal-based meat, it could rapidly take market share and produce a triple dividend of reduced carbon emissions, land-use and lower consumer prices.

335 This will be discussed in further detail in the section on Stranded Assets.
336 Way et al. (forthcoming). "Cost of the Green Transition" Institute of New Economic Thinking. Working Paper.
337 Hoyer (2019). "Without private finance, there will be no green transition. Here is what needs to happen". World Economic Forum.
338 Climate Finance Leadership Initiative (2019). "Financing the Low-Carbon Future: A Private-Sector View on Mobilizing Climate Finance".
339 IISD and GSI (2019) Fossil Fuel to Clean Energy Subsidy Swaps: How to Pay for an Energy Revolution, Geneva, Switzerland.
340 Ibid.
341 More about this project can be found at: https://www.hybritdevelopment.com/

In many cases, the private sector can work with governments to create a more favourable climate for green investment. Engaging with local governments to set up power-purchase agreements, currency hedging instruments and mechanisms to uncover consumer creditworthiness can help propel green investment. Public-private partnerships offer an opportunity for collaboration.

For riskier green projects, blended finance options that partially de-risk investment can entice private funding. These can include currency hedging, government support and country risk guarantees (see Fig. 16).[342] For example, a government whose country has a volatile currency could offer power purchase agreements in dollars and use its own currency reserves to offset currency risks. Governments may be incentivised to take on this risk because it helps meet the goal of building out renewable energy infrastructure, with the benefit that reduced dependence on fossil fuels could lessen their exposure to shifts in international fuel prices. In general, under "blended finance" approaches, small amounts of concessional government or donor funds are used to lower the risk of high-impact investments that can advance climate change mitigation and over time become commercially viable without support.

FIG.16

FIVE WAYS PUBLIC SECTOR CAN GALVANISE MORE PRIVATE FINANCE IN EMERGING MARKETS

DIFFICULTY EVALUATING MULTIPLE, OVERLAPPING RISKS With limited time and numerous alternatives, private sector finds it difficult to fully evaluate risks of low-carbon investments.	PUBLIC SECTOR TAKES FIRST LOSS EQUITY POSITION Public sector takes equity stakes in a way that increases the number of projects that can fail before private investor loses money
DEAL FLOW PROBLEMS Insufficient number of commercially attractive, easily executable deals.	CREATE LOW-CARBON DEVELOPMENT COMPANIES Create publicly funded, privately run bodies that engage in low-carbon project develoment (securing consents, PPA negotiation)
CURRENCY RISK Exchange risk fluctuations make returns volatile and potentially undermine profitability of investment	ESTABLISH CURRENCY FUNDS OFFERING HEDGING PROJECTS Use public money to establish funds that offer investor hedges for less well traded currencies. Build on TCX experience
LOW-CARBON POLICY RISK Possibility that policies underpinning investments in low-carbon solutions will be reversed or countered in some way	OFFER LOW-CARBON POLICY RISK COVER Make financial instruments to cover the risks of policy reversals and dilution
COUNTRY RISK Institutional investors committing capital to funds may not know if their projects will be exposed to country risks	MAKE COUNTRY RISK GUARANTEES MORE EXPLICIT Allow funds to secure "in principle" country risk cover before raising capital from institutional investors

Source: Adapted from UNEP (2009) Catalysing Low-Carbon Growth in Developing Countries.

342 Ibid.

The following questions can be useful to discern how a low-carbon alternative could overtake conventional investment:

- Cost competitiveness with substitutes: is there a low-carbon technology that is consistently becoming cheaper while the conventional option remains stagnant in terms of cost?
- Potential to change the market paradigm: does the investment have the potential to disrupt the market? Can it produce a high-value patent?
- Government commitment to promoting a given technology: does the government have policies in place to incentivise investment in a specific (sub)sector? Policies can include guaranteed tariffs, tax credits, purchase obligations, etc. Is the current political climate stable enough to last the lifetime of the project?
- Scope to "shape and make" the market: are local policymakers open to dialogue and to putting in place provisions to ensure an improving investment climate?
- International risks: are key import or export markets considering border carbon adjustments (i.e. additional tariffs on goods from countries that do not have domestic carbon pricing)? If so, consider whether carbon-intensive investments have long-term durability.

3.3. Levers of change for climate finance and low-carbon investments

In this section, we discuss three main levers of change that we think could contribute to the development of climate finance in a world post Covid-19:

- Changes in the evaluation of portfolio risks
- A reduction in fossil fuel subsidies
- An active engagement of central banks towards green finance

3.3.1. Private-sector re-evaluation of portfolio risks

The lockdown policies during the coronavirus pandemic have dramatically affected heavily polluting industries. Oil prices plummeted to an 18-year low, and if this crisis lasts, the impact on the profitability of fossil fuel industries will be severe. Depressed demand has hit asset utilisation in the energy sector, which has been particularly problematic for thermal power plants that require high levels of asset utilisation. Other industries have also been affected – aviation is set to lose USD84 billion in 2020.[343] Hundreds of thousands of jobs are at risk, with all airlines announcing drastic job cuts. For instance, EasyJet plans to cut up to 30 per cent of its staff.[344]

The pandemic has served as a reminder that funds must be devoted to sectors that are responsible stewards of capital, resilient against future risks and compatible with structural change. The extraordinary decline in the oil price has underscored the importance of investing in flexible assets. Oil fields, once operational, cannot simply be switched off – a fact that catapulted prices in the oil futures market into negative territory, to the dismay of investors. The fallout potential is sizeable: 20 to 30 per cent of market capitalisation in the stock exchanges of London, San Paolo, Moscow, Australia and Toronto is closely linked to fossil fuels.[345]

343 BBC News (2020) Coronavirus: Airlines set for 'worst' year on record. 9 June 2020.
344 Partridge, J. (2020) EasyJet plans to cut up to 30% of staff as Covid-19 hits demand. The Guardian, 28 May 2020.
345 Carbon Tracker Initiative (2017). 2 Degrees of Separation: Transition Risk for Oil and Gas in a Low-Carbon World. Available at: https://carbontracker.org/reports/2-degrees-of-separation-transition-risk-for-oil-and-gas-in-a-low-carbon-world-2/; Van der Ploeg, R., & Rezai, A. (2019). Stranded Assets In The Transition To A Carbon-Free Economy (No. 894).

There will be little merit in investing in assets that cannot flexibly adapt to changing conditions or be retrofitted, considering the uncertain future where demand may slump again or be further cannibalised by electric vehicles, low-cost batteries, affordable renewable energy and breakthroughs in green hydrogen/ammonia.[346]

Credible pursuit of the Paris Climate Accord requires a significant reduction in fossil fuel extraction. To achieve its goals, about 80 per cent of existing coal reserves, half of the gas reserves and a third of the oil reserves should be left in the ground.[347] It is forecast that the amount of fossil fuels in the pipeline by 2030 will be 50 per cent higher than what would be consistent with a 2°C pathway, and 120 per cent higher than what would be compatible with a 1.5°C degree target.[348] The pandemic has shone light on the riskiness of such investments and the vulnerable position of those companies that have staked their futures on the fossil fuel industry. Overall, the value of top 13 international oil companies could decrease by about USD360 billion should conditions be put in place to limit global warming to 2°C and by nearly USD890 billion in a 1.5°C world.[349] This is why companies have a fiduciary duty to their investors to be explicit about their balance sheet projections across various climate scenarios.

Around USD20 trillion of long-lived polluting assets are at risk of becoming obsolete as climate action is accelerated. Research suggests that existing assets already have the capacity to burn enough fossil fuels for global warming to reach 1.5°C by 2100 (see Fig. 17).[350] This problem will be critical in emerging markets relying on coal and carbon-intensive sectors. The top two countries with the highest shares of worldwide committed emissions are China (41 per cent) and India (nearly 9 per cent).[351] The economic value of global CO_2-emitting energy infrastructure, including electricity, industry, transport, residential and commercial sectors, is estimated at USD22 trillion.[352] The low-carbon transition could make many fossil fuel assets worthless, sending ripples throughout the financial sector and impacting shareholders. The entire fossil fuel value chain is exposed to transition risk: this includes upstream

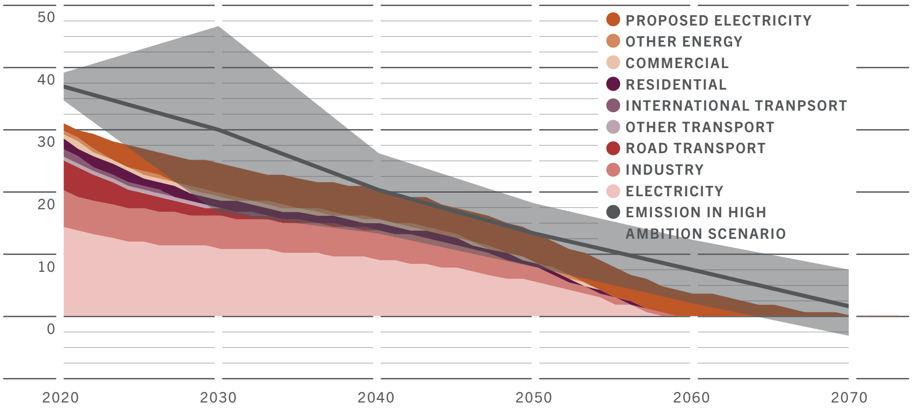
346 Pfeiffer, A., Millar, R., Hepburn, C., & Beinhocker, E. (2016). The '2°C capital stock' for electricity generation: Committed cumulative carbon emissions from the electricity generation sector and the transition to a green economy. Applied Energy, 179, 1395-1408.
347 McGlade, C., & Ekins, P. (2015). The geographical distribution of fossil fuels unused when limiting global warming to 2°C. Nature, 517(7533), 187-190.
348 UN Environment (2019). Production Gap 2019. Available at: https://www.unenvironment.org/resources/report/production-gap-report-2019
349 Livsey, A. (2020). Lex in depth: the $900bn cost of 'stranded energy assets'. Financial Times. Available at: https://www.ft.com/content/95efca74-4299-11ea-a43a-c4b328d9061c
350 Tong et al. (2019). Committed emissions from existing energy infrastructure jeopardize 1.5°C climate target. Nature, 572(7769), 373-377.
351 Ibid.
352 Ibid.

industries that extract fossil fuels and downstream users such as power plants, cement, steel, aviation, shipping and road transportation. Low-carbon solutions in these industries are available but need much more active pursuit and financing.

The future committed CO2 emissions are estimated by assuming historical lifetimes and utilisation rates for infrastructure and assets.

FIG.17

COMMITTED ANNUAL ENERGY AND INDUSTRIAL CO_2 EMISSIONS AGAINST EMISSIONS ASSOCIATED WITH THE HIGH-AMBITION WARMING SCENARIO, GT CO_2 PER YEAR



Source: The data for future CO_2 emissions is reproduced from Tong et al. (2019) and the data for the High-Ambition emission

Political risks are also emerging. As extreme weather events become more commonplace, the salience of climate change increases and the impetus to act becomes stronger. Climate change litigation risk is emerging as an important consideration.[353] One such example is the case against a large energy company, RWE, in Germany, where activists from BUND challenged the destruction of a forest for increased lignite mining. Climate litigation is expanding across jurisdictions, and claims are being pursued by investors, activist shareholders, cities and states. [354] Evidence supporting these cases is growing, as scientists are able to link extreme weather events to climate change in a causal manner, which increases political and regulatory risks to carbon-intensive companies. In the early 2000s hardly any climate change litigation cases made their way into American courts. Over the years this has dramatically changed. Sixty cases were brought in 2010 and over 100 cases were put forward in 2015.[355] Investors and fossil fuel companies must therefore reckon with a new type of risk: litigation. While most litigation cases have happened either in the US or in high-income countries, the number of legal cases in low- and middle-income countries is grow-

353 Setzer J and Byrnes R (2019) Global trends in climate change litigation: 2019 snapshot. London: Grantham Research Institute on Climate Change and the Environment and Centre for Climate Change Economics and Policy, London School of Economics and Political Science.
354 Setzer J and Byrnes R (2019) Global trends in climate change litigation: 2019 snapshot. London: Grantham Research Institute on Climate Change and the Environment and Centre for Climate Change Economics and Policy, London School of Economics and Political Science. Ibid.
355 Ibid.

ing. There have been cases in Pakistan, India, the Philippines, Indonesia, South Africa, Columbia and Brazil.[356]

Financial markets need to be much more transparent about their exposure to fossil fuel-related risks. Transition risk, particularly the early retirement of carbon-intensive assets, poses a significant risk to institutional investors, including pension funds. The disclosure recommendations developed by the Financial Stability Board Task Force on Climate-related Financial Disclosures (TCFD) provide a set of rules to facilitate disclosure. These guidelines have been used by more than 340 investors with nearly USD34 trillion assets under management.[357] More than 10 governments and financial regulators have either endorsed the TCFD recommendations or consulted on incorporating them into existing disclosure regulation.[358] The impetus to act comes from a growing awareness of the severity of asset stranding. Estimates suggest that the European financial sector may be exposed to more than EUR1 trillion worth of fossil fuel assets, and the potential losses from asset stranding could be between EUR350 billion and EUR400 billion.[359]

For investors that have stakes in assets at high risk of stranding, portfolio restructuring and investments in retrofitting could help manage exposure. Investors that are highly exposed to climate change transition risks may consider restructuring their portfolios by diversifying into industries that are likely to gain market share in a carbon-constrained world. A hedging approach would involve betting on sectors that facilitate the green transition. The European Patent Office's categorisation of green technologies offers insights into what some of these "winning" technologies/sectors may be.[360] Retrofitting existing plants with energy-efficient technologies or adopting negative emissions technologies could be another approach, albeit potentially riskier. Carbon capture and storage (CCS) is one such option. CCS is still under development, and the cost of CCS retrofits is uncertain. Nevertheless, it is an often-discussed option as it may help prevent some of the asset stranding mentioned above. CCS could become widely used in the emerging markets that possess a large stock of coal-fired power plants. According to an IEA analysis, about 385 GW of China's coal power capacity could find suitable CO_2 storage sites within a 250 km radius and

356 Ibid.

357 Task Force on Climate-related Financial Disclosures (2019). TCFD: 2019 Status Report. Available at: https://www.fsb-tcfd.org/publications/tcfd-2019-status-report/#

358 Principles for Responsible Investment (2019). Climate-related disclosure. Available at: https://www.unpri.org/climate-change/climate-related-disclosure-/3971.article

359 Weyzig, F., Kuepper, B., van Gelder, J. W., & van Tilburg, R. (2014). The price of doing too little too late. The impact of the carbon bubble on the EU financial system, Green European Foundation, Brussels.

360 See: https://worldwide.espacenet.com/classification?locale=en_EP#!/CPC=Y02 (consulted 7 September 2020)

about 310 GW of existing coal-fired electricity capacity are suitable for a CCS retrofit[361]. China also has several CCS demonstration projects in different stages of advancement, including, the Huaneng Shanghai Shidongkou 2nd Power Plant (with a capture capacity of between 100,000 and 120,000 tonnes per annum of CO_2.[362]

Other retrofit options, like coal-to-biomass, may prove to be more technically feasible, as they rely on more tried and tested solutions.[363] In the future, if CCS were to be combined with biomass, the so-called bio-energy and CCS (BECCS) process might be able to deliver net-negative emissions (as CO_2 is captured from the atmosphere during biomass growth and then CCS prevents emissions from going to the atmosphere during combustion).[364] In China, bioenergy could also become widely used. Coal-bioenergy gasification systems could tackle climate change and air pollution at the same time, with carbon capture and storage in regions that are rich in crop residues.

Large-scale deployment of negative emissions technologies (NETs) might be necessary to prevent 2°C of warming. NETs include a wide range of technologies such as***:*** forest-management (afforestation and reforestation), direct air-capture and storage, soil carbon sequestration, bio-char, ocean fertilisation, etc.[365] India and China are already taking steps in the large-scale deployment of NETs.[366] China alone accounts for 25 per cent of the global increase in leaf area from 2000 to 2017, of which 42 per cent can be attributed to forests. Offset markets could develop and allow large corporations to pay for their CO_2 emissions through investment in NETs. However, investment in NETs should not be seen as a licence to keep emitting CO_2. Both large-scale deployment of NETs and rapid emission reductions are required to limit temperature increases to well below 2°C.[367] Moreover, the potential of NETs at scale may be limited by socioeconomic and technical factors, including in some instances the large areas of land required.[368]

361 IEA (2017) The potential for carbon capture and storage in China (Available at: https://www.iea.org/news/the-potential-for-carbon-capture-and-storage-in-china)

362 Global CCS Institute (2018) Carbon capture and storage in de-carbonising the Chinese economy (available at: https://www.globalccsinstitute.com/news-media/insights/carbon-capture-and-storage-in-de-carbonising-the-chinese-economy/)

363 Lu, Xi, et al. "Gasification of coal and biomass as a net carbon-negative power source for environment-friendly electricity generation in China." Proceedings of the National Academy of Sciences 116.17 (2019): 8206-8213.

364 McKechnie, J., Saville, B., & MacLean, H. L. (2016). Steam-treated wood pellets: Environmental and financial implications relative to fossil fuels and conventional pellets for electricity generation. Applied energy, 180, 637-649; Keller et al. (2018). Coal-to-biomass retrofit in Alberta–value of forest residue bioenergy in the electricity system. Renewable energy, 125, 373-383.

365 Fuss et al. (2016). Research priorities for negative emissions. Environmental Research Letters, 11(11), 115007.

366 Chen et al. (2019). China and India lead in greening of the world through land-use management. Nature Sustainability, 2(2), 122-129.

367 Hepburn, Cameron, et al. "The technological and economic prospects for CO_2 utilization and removal." Nature 575.7781 (2019): 87-97.

368 Rogelj et al. (2015). Energy system transformations for limiting end-of-century warming to below 1.5°C. Nature Climate Change, 5(6), 519.

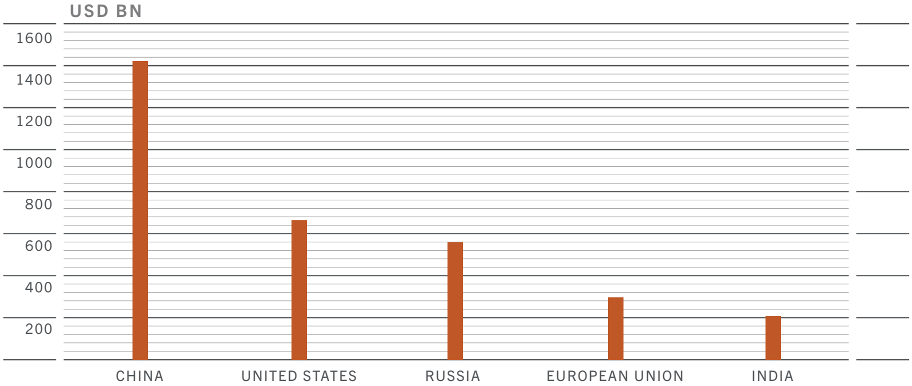
3.3.2. Phasing out fossil fuel subsidies

The opportunity of a green recovery from the coronavirus pandemic has reignited the longstanding debate on reducing subsidies to carbon-intensive industries. Fossil fuel subsidies can come in many forms. Some common examples include selling fossil fuels below the market rate,[369] offering land at heavily subsidised rates, ignoring third-party costs such as air pollution, water pollution and carbon emissions, and putting in place tax exemptions.[370] Fossil fuel subsidies amounted to 6.5 per cent of global GDP in 2015, totalling USD5 trillion.[371] The largest subsidisers were China (USD1.4 trillion), United States (USD649 billion), Russia (USD551 billion), European Union (USD289 billion) and India (USD209 billion), as shown in Fig. 18.[372] The pursuit of policies to promote renewable energy while at the same time subsidising fossil fuels sends mixed signals and has been a significant hurdle to the low-carbon transition over the past decades.

Low oil prices have in the past created the right political conditions to reduce subsidies in oil-producing jurisdictions.[373] Politicians have strategically decreased domestic subsidies in times of low international oil prices, judging that consumers would be less likely to feel the impact. Today's conditions present another such opportunity.

FIG.18

COAL SUBSIDIES IN 2015, USD BN



Source: Coady, D., Parry, I., Le, N.-P. and Shang, B. (2019) Global Fossil Fuel Subsidies Remain Large: An Update Based on Country-Level Estimates. International Monetary Fund Working Paper 19/89.

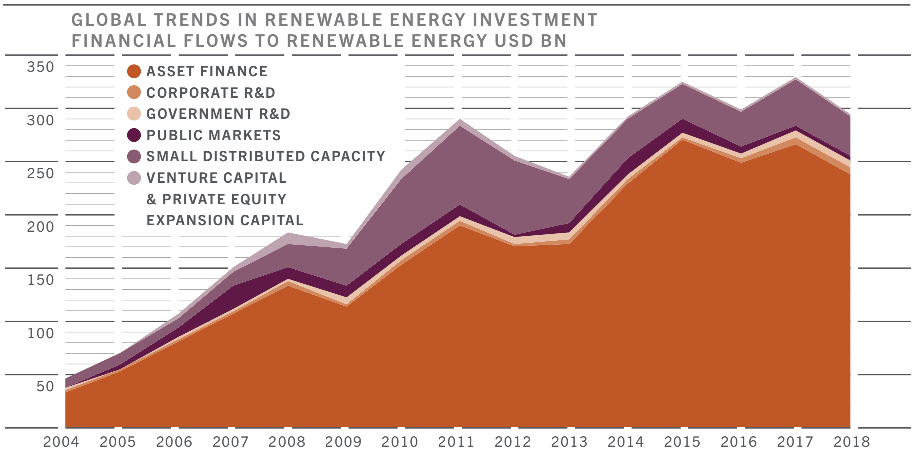
369 Victor, D. G. (2009). The politics of fossil fuel subsidies. Available at SSRN 1520984.
370 Coady, D., Parry, I., Sears, L., & Shang, B. (2017). How large are global fossil fuel subsidies?. World development, 91, 11-27.
371 Ibid.
372 Ibid.
373 Krane, J. (2018). Political enablers of energy subsidy reform in Middle Eastern oil exporters. Nature Energy, 3(7), 547-552.

Phasing out subsidies for fossil fuels can help governments tap into a growing pool of climate finance (Fig. 19). Annual flows of climate finance from public and private sources reached USD580 billion in 2017/2018, representing a 25 per cent increase from the year before.[374] The issuance of green bonds has similarly grown – from less than USD1 billion in 2009 to USD260 billion in 2019.[375] However, the transition to a low-carbon world needs an estimated USD6 trillion per year, highlighting the need to galvanise more capital.[376] At the same time, international finance for fossil fuel investments is drying up. Many major multilateral finance institutions such as the World Bank and the EBRD are no longer financing new coal projects.[377] Following their lead are insurers such as Axa and Allianz, who understand the risks of asset stranding, as well as BlackRock – the world's largest fund manager – who have said they will exit investments in thermal coal. This shift in the global finance community should be mirrored in the actions of governments.

Government support for clean energy investments would benefit from consistency. Governments in emerging markets have sometimes wavered on their support for clean energy and green investments. Thirty-one per cent of respondents in a poll of more than 2,000 business leaders across the G20 said that a lack of government support poses a significant barrier to low-carbon investments.[378] Actions like the local government reneging on wind power purchase agreements in Andhra Pradesh[379] and Brazil increasing deforestation shake investor confidence. By contrast, when countries or states provide more stable policy signals, investment flows in at a lower cost of capital and in larger volumes.

374 CPI (2019). Global Landscape of Climate Finance 2019 [Barbara Buchner, Alex Clark, Angela Falconer, Rob Macquarie, Chavi Meattle, Rowena Tolentino, Cooper Wetherbee]. Climate Policy Initiative, London.
375 Climate Bonds Initiative, 2020.
376 New Climate Economy (2014). "Infrastructure Investment Needs of a Low-Carbon Scenario"
377 Kynge, J. and Hook, L. (2018) "Development bank halts coal financing to combat climate change". Financial Times.
378 Ahurst (2020) "Powering Change: Energy in Transition"
379 Chatterjee, A. (Oct 2019). "After Andhra Pradesh, it's Uttar Pradesh's turn to flout renewable PPAs. Financial Express

FIG.19



Source: Frankfurt School-UNEP Centre/BNEF. (2019).
Global Trends in Renewable Energy Investment 2019. Chapter 2

Finally, investing in adaptation can partially offset the increase in the cost of capital caused by the rising physical risks of climate change. The increased frequency of droughts is impacting water-dependent activities such as thermal power and hydroelectricity generation in Brazil and India.[380] A rising sea level is increasing the risks associated with coastal development in Vietnam.[381] Econometric modelling suggests that climate vulnerability has already raised the average cost of debt in developing countries by 117 basis points. In absolute terms, this translates into USD40 billion of additional interest payments over the past 10 years on their government debt alone. And while "no downgrade by a major credit rating agency has been attributed to climate risks (explicitly), sovereign credit ratings are likely to be incorporating (climate) risks in their assessments (implicitly)."[382] Emerging market investors and governments can reduce some of this risk by actively pursuing adaptive investments, potentially in tandem with regular investments. For example, coastal development can be accompanied by mangrove reforestation, which naturally reduces inundation risk. Municipal investment can be accompanied by the creation of green space to reduce the urban heat island effect. Governments can engage in upstream reforestation to minimise the risk of downstream flooding. Investment in green infrastructure through nature-based solutions can yield a double dividend of reducing carbon emissions and increasing resilience.

380 de Jong, P., Tanajura, C. A. S., Sánchez, A. S., Dargaville, R., Kiperstok, A., & Torres, E. A. (2018). Hydroelectric production from Brazil's São Francisco River could cease due to climate change and inter-annual variability. Science of the Total Environment, 634, 1540-1553.

381 Balboni, C. (2018). In harm's way. Infrastructure Investments and the Persistence of Coastal Cities.

382 Imperial College Business School and SOAS University of London (2018) "Climate Change and the Cost of Capital in Developing Countries". Commissioned by UN Environment with funding from MAVA Foundation.

3.3.3. Central banks can help

Central bankers can play a key role in the post Covid-19 recovery by ensuring that there are incentives to direct funds towards green sectors which can minimise systemic risk. Traditionally viewed as neutral entities, there has been little scope for central banks to support particular technologies or sectors. However, given the increasing recognition that climate change presents a system-level risk, some central banks are thinking about their role in stemming the economy's exposure to the physical and transition risks associated with climate change, particularly given the pandemic-fuelled collapse in oil prices and transport demand. As Mark Carney, the former governor of the Bank of England termed it, "financial markets are experiencing the 'tragedy of the horizon'," [383] a situation in which risks that are material for physical assets are not necessarily material for investors and hence not always priced in by financial analysts. Fossil fuel investments face new risks, which include climate litigation,[384] climate policy, asset stranding, under-utilisation and international backlash through the growing adoption of net-zero commitments. A survey of 231 central bank officials, finance ministry officials, and other economic experts from G20 countries reveals that there are five policies with high potential on both economic multiplier and climate impact metrics: clean physical infrastructure, building efficiency retrofits, investment in education and training, natural capital investment and clean R&D.[385]

Several central banks have recognised climate change as a serious system-level risk and have taken action. In 2017, the Bank of Italy launched a national dialogue on sustainable finance to share knowledge on climate-related risks. In 2019, the Bank of England set requirements for insurance companies, banks and investors to disclose climate-related risks. The Bangladesh Bank and the Bank of Japan have offered additional liquidity and subsidies to banks that lend to green projects. The Reserve Bank of India has set preferential quotas for borrowing by investors in environmentally friendly sectors.[386]

383 Tragedy of the Horizon: http://tragedyofthehorizon.com/

384 Rafaty, R., Srivastav, S., & Hoops, B. (2020). Revoking coal mining permits: an economic and legal analysis. Climate Policy, 1-17.

385 Hepburn, C., O'Callaghan, B., Stern, N., Stiglitz, J., & Zenghelis, D. (2020). Will Covid-19 fiscal recovery packages accelerate or retard progress on climate change?. Oxford Review of Economic Policy, 36.

386 Campiglio, E. (2016). Beyond carbon pricing: The role of banking and monetary policy in financing the transition to a low-carbon economy. Ecological Economics: The Journal of the International Society for Ecological Economics , 121 , 220–230

It is within the remit of central banks to correct for "information-related market failures" so that investors are cognisant of the risks related to investing in fossil infrastructure. Mark Carney has pointed to the possibility of a "climate Minsky moment", where investors suddenly abandon fossil fuel assets as governments belatedly act to prevent global warming and meet the goals of the Paris Agreement. The volume of oil- and gas-linked assets outstanding means such a shift could destabilise the whole financial system.[387] To this end, the UK's Financial Stability Board's Task Force on Climate-Related Financial Disclosures (TCFD) has developed recommendations for building climate resilience.[388] These measures require corporations to adequately disclose their modelling assumptions and exposure to both physical and transition risks, and enjoy widespread support among the financial community.[389]

Other more interventionist ideas include green quantitative easing (QE). The basic idea of green QE is that asset purchases would be redirected towards green bonds (including buying corporate bonds directly from renewable energy companies and other firms pursuing low-carbon technologies). This is a way for central banks to lend to green industries. Green QE could boost long-term social returns and create positive "lock-in" effects from investment in long-lived low-carbon capital stock. It would also, like normal stimulus packages, come with fiscal and employment multipliers.[390] The challenge for those arguing for green QE, however, is to clearly specify the division of responsibility between central banks and finance ministries. Financing specific actions in specific parts of the economy is normally within the remit of the finance ministry, rather than the central bank.

Some central banks are exploring the idea of preferential lending rates for green projects. Hungary's central bank became Europe's first monetary authority (in 2020) to put forward a preferential capital requirement programme for credit institutions to support the growth of green financial products and to improve the energy efficiency of the Hungarian building stock.[391]

Stronger involvement by central banks in the climate agenda could help shore up more private finance for climate change investments. Strong statements from central banks around the world are signalling the beginning of an important shift – one in which climate change is recog-

387 Financial Times (2019) "How central banks can tackle climate change".
388 TCFD. (2017). "Final Report: Recommendations of the Task Force on Climate-related Financial Disclosures"
389 Ibid
390 Bowen, A., Fankhauser, S., Stern, N., & Zenghelis, D. (2009). An outline of the case for a 'green'stimulus.
391 ECBC (2019). "Hungarian central bank introduces a green preferential capital requirement program".

nised as a system-level risk that needs management. As representatives of the Bank of England have said, "forming a strategic response to the financial risks from climate change helps ensure the Bank can fulfil its mission to maintain monetary and financial stability, both now and for the long term."[392] This signals to investors that the climate for low-carbon finance is improving; it also indicates that disclosure requirements will be strengthened over time such that current and future investments are climate-compatible. How this will impact future stock market valuations for fossil fuel assets remains to be seen but these are important trends that should factor into decision-making by investors, shareholders and asset managers.

392 Scott, Matthew and Van Huizen, Julia and Jung, Carsten, The Bank's Response to Climate Change (16 June 2017). Bank of England Quarterly Bulletin 2017 Q2. Available at SSRN: https://ssrn.com/abstract=3004461

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Conclusion

This report identifies major challenges for the global economy as it deals with environmental degradation. It estimates that unmitigated climate change would cost the world 45 per cent of its GDP per capita compared to a baseline of no climate change by the end of the century. This is a larger impact than the global financial crises, the Great Depression, or the likely impact of Covid-19, and, even so, may well be an underestimate for reasons set out in the Appendix. Climate change is certain to disrupt key sectors of the economy, including agriculture and energy. And the sheer value of assets that are exposed to risks of climate change or the low-carbon transition could destabilise the world's financial system.

Global and regional estimates from our modelling work, as well as from a thorough review of the economic and environmental literature, suggest that emerging market economies will bear the brunt of much of these impacts because of the structure of their economies and geographies. Many emerging markets are still directly or indirectly critically dependent on climate-sensitive sectors. They also have populations exposed to temperature extremes. Apart from Russia – which is one of the world's coldest countries – all the emerging economies analysed in this report will be clear net losers under climate change. Even in the case of Russia, we have not assessed the full impact of the knock-on effect that a weak global economy could have on the Russian economy.

Ten years ago, the question was whether emerging market economies should engage in climate change mitigation or wait for the high-income countries to take the lead. A common argument made at that time in these countries was "grow now and clean up later." Yet even then, studies concluded that early action was advisable to avoid the worst of the damage climate change will cause.

Today is the time for action. Unless measures are taken in the coming decade, climate change could very well become irremediable. Furthermore, governments are now engaging in large-scale recovery programmes and are investing billions of dollars – measures that will shape the global economy for years to come.

As climate damages become more apparent, and green alternatives continue to become cheaper, the question is not whether to act, nor even to what degree. It is clear emerging economies need to act quickly and aggressively.

They must not be passive. The effects of climate change on emerging economies will to a huge extent be determined by their own actions.

Investment in fossil fuel assets has slowed but not enough, especially in emerging markets, putting pressure on the climate's stability. These investments also put the financial sector and investors at risk: 20-30 per cent of market capitalisation in major stock exchanges is closely linked to fossil fuels.[393] The recent collapse in the oil price to as low as USD25 per barrel suggests the likely future degree of volatility in the fossil sector as key players adjust to a new reality.

The green recovery post Covid-19 will be sustained by three trends that have become evident over the past few years:

— The technological landscape has evolved rapidly in favour of clean alternatives, reducing the attractiveness of fossil fuels. Markets will continue to move towards clean technologies given their risk / return characteristics.
— Climate change negotiations have made progress in only a few years and pressure has been growing for more countries to act on climate change.
— Financial innovation to support green alternatives has been increasing rapidly and is leading to ever cheaper green technologies.

393 Carbon Tracker Initiative (2017). 2 Degrees of Separation: Transition Risk for Oil and Gas in a Low-Carbon World. Available at: https://carbontracker.org/reports/2-degrees-of-separation-transition-risk-for-oil-and-gas-in-a-low-carbon-world-2/; Van der Ploeg, R., & Rezai, A. (2019). Stranded Assets In The Transition To A Carbon-Free Economy (No. 894).

Investors in a green recovery post Covid-19 may want to consider the following questions:

1. ***Are returns commensurable with risks of fossil investment?*** Fossil fuel assets are risky. Returns should be assessed against the risks that they entail in the future. The recent collapse in the oil price provides an illustration of the risks in the sector. As discussed in this report, the risks to fossil fuel assets include stranding, lower utilisation rates, climate policy and litigation. For the same level of profitability, low-carbon technologies are likely to be a much safer bet.
2. ***Do companies understand and disclose their climate change exposure?*** Investors should know about the risks they take. The implications that climate change could have on a business can be extremely complex since many effects will be indirect.
3. ***Which emerging market countries have a coherent low-carbon transition plan?*** Countries that do not plan for the low-carbon transition are taking big risks, too. They are not favouring the commercial and industrial environment that will be resilient to climate disruptions. They could potentially be locking themselves in technologies that will be outdated and, eventually, become stranded. When investors decide to divest from fossil fuels, countries seen as pollution havens could see foreign direct investment evaporate and be exposed to severe macroeconomic disruptions.
4. ***Would portfolios yield higher long-term returns with stronger climate action?*** The economic losses from climate change could be so large that many investors, even those that have interests in assets related to fossil fuels, are likely to be better off by acting aggressively against climate change than having to suffer the damages inherent to their portfolios from inaction. This may particularly be the case in emerging market economies since these are likely to be more vulnerable.
5. ***Are sensible adaptation and insurance measures in place?*** Some of the negative impacts of climate change can be addressed if proper adaptation measures are put in place. Extensive risk assessments and cost benefit analyses will be needed to identify the best adaptation strategies. Nature-based solutions and early warning systems are some relatively cheap ways to achieve very favourable adaptation outcomes and risk reductions. Also, insurance products constitute a valid adaptation strategy in themselves.

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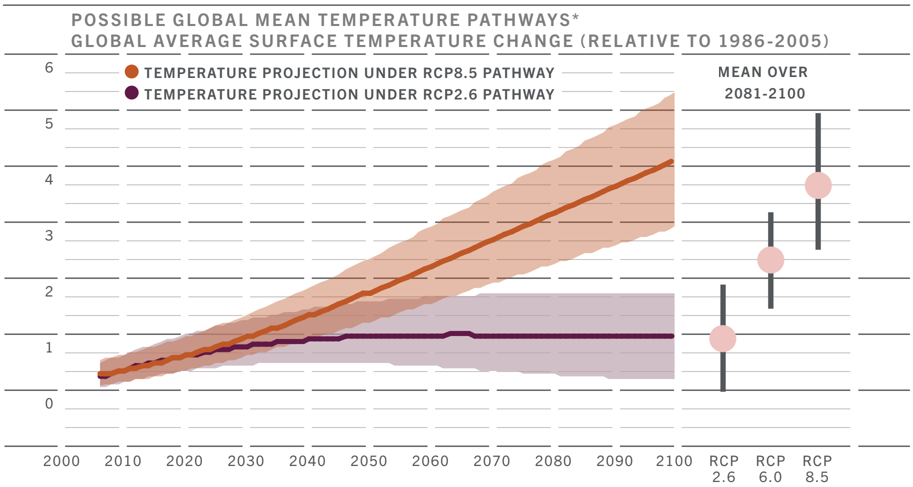
Appendix
Global climate risk analysis methodology

This section provides details on the methodology associated with the estimates of global economic costs or risks associated with climate change to the end of the century.

Global-Warming Scenarios

To capture the uncertainty around future warming trajectories we use three possible scenarios of future warming (Fig. 20), inspired by the most common temperature scenarios used by the IPCC[394] and the wider modelling community. We considered the full range of the climate models used in the 5th Coupled Model Intercomparison Projection (CMIP5) to identify the temperature scenarios that would offer the most insights for this report.

FIG.20



*The mean indication over 2081-2100 was used to determine the projected temperature by the end of the century in this report. Forecast changes under IPCC global-warming scenarios identified are based on the Representative Concentration Pathways (RCPs) developed for the IPCC to describe different climate futures based on different trajectories of greenhouse gas emissions

Source: Based on IPCC Synthesis Report 2014. Core Writing Team, R. K. Pachauri, and L. Meyer, Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 1. Geneva, Switzerland, 2014, vol. 40, isbn: 9789291691432. doi: 10.1046/j.1365-2559.2002.1340a.x. [Online]. Available: http://doi.wiley.com/10.1046/j.1365-2559.2002.1340a.x.Huppmann, D., Kriegler, E., Krey, V., Riahi, K., Rogelj, J., Rose, S. K., ... & Calvin, K. (2018). IAMC 1.5 C Scenario Explorer and Data hosted by IIASA. Integrated Assessment Modeling Consortium & International Institute for Applied Systems Analysis.

394 Core Writing Team, R. K. Pachauri, and L. Meyer, Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 1. Geneva, Switzerland, 2014, vol. 40. Available at: http://doi.wiley.com/10.1046/j.1365-2559.2002.1340a.x.

The three global-warming scenarios identified are based on the Representative Concentration Pathways (RCPs) developed for the IPCC[395] to describe different climate futures based on different trajectories of greenhouse gas emissions. They are as follows:

High-Ambition Scenario (RCP 2.6)

The 'high-ambition' scenario involves immediate mitigation action aimed at halting increasing atmospheric greenhouse gas concentrations at levels of 450 ppm by the end of the century. Global cooperation in this scenario starts immediately with all countries committing to mitigation efforts, with aggressive action on demand management and costs in new clean technologies continuing to decline. This scenario involves a radiative forcing of 2.6 W/m^2 (watts per square meter) by the end of the century, resulting in global temperatures stabilising at around 1.6°C[396] above pre-industrial levels (Fig. 20).

Current Policies Scenario (RCP 6.0)

The 'current policies' scenario tries to capture the main elements of the existing climate policy landscape by including current emission reduction commitments and renewable or nuclear energy technology targets. This might be considered a "base case" scenario and tracks well to current policies[397] and a scenario in which G20 Annex 1 countries take primary responsibility for mitigating climate change. This scenario results in radiative forcing of 6.0 W/m^2 and generates 2.8°C of warming above pre-industrial levels by the end of the century, with temperatures continuing to rise into the next century.

Worst-Case Scenario (RCP 8.5)

The 'worst-case' scenario is a world in which no country pursues any new policies dedicated to climate change mitigation. This scenario is considered somewhat unrealistic[398] and simply represents a counterfactual for the other two policy-related scenarios. The average warming generated from the models for this scenario is 4.3°C above pre-industrial levels, associated with a radiative forcing of 8.5 W/m^2 by 2100, with temperatures continuing to rise into the next century.

395 van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., … Rose, S. K. 2011. The representative concentration pathways: An overview. Climatic Change, 109, 5–31.

396 The end-of-century global temperature estimates are taken from Table 2.1 in the IPCC Synthesis Report 2014 and are based on the full range of CMIP5 models.

397 Given that both the Climate Action Tracker and the UNEP Emissions Gap Report argue current levels of ambition would result in about 2.9°C - 3°C of warming by the end of the century, we were confident to consider this scenario the 'current policies' scenario.

398 This scenario is considered unlikely as it relies on virtually no continuation of the strong advancements currently occurring with renewable technologies and does not account for the impact that warming will have on economic growth at such high temperatures. It is hard to imagine that most economies will be able to function well (and continue to emit GHGs at such high rates) under the extremes of droughts, wildfires, hurricanes, and floods that this scenario would entail.

Shared Socioeconomic Pathways

The Shared Socioeconomic Pathways (SSPs) are a family of five modelled socioeconomic pathways of global change that each draw on several plausible ways societies might evolve through the 21st century. These pathways can be summarised as follows:

SSP1: Sustainability (Taking the Green Road) involves the world shifting gradually towards a sustainable path with inclusive development and a respect for the world's environmental limits.

SSP2: Middle of the Road consists of a world following a path in which social, economic, and technological trends follow historical patterns including growth inequality.

SSP3: Regional Rivalry (A Rocky Road) sees resurgent nationalism and concerns about competitiveness and security leading to regional conflicts and is characterised by high population growth, resource-intensive consumption, and limited regulation of land-use change.

SSP4: Inequality (A Road Divided) involves increasing disparities in economic opportunity and political power, leading to increasing inequalities and stratification both across and within countries.

SSP5: Fossil-fuelled Development (Taking the Highway) involves lower population growth and increased faith in competitive markets, international market integration, and participatory societies that produce rapid technological progress but with continued exploitation of fossil fuel resources.

Each of the SSPs can be situated relative to the others based on their level of mitigation and the adaptation challenges contained within them. For example, the SSP4 scenario assumes that the population succeeds in limiting its GHG emissions but that the climate change caused by the lower levels of GHG emitted has relatively large impact due to difficulties with adaptation efforts.

Each SSP scenario is composed of a baseline scenario where no policies are taken and no climate change damages occur, and the system evolves only because of the social and economic assumptions of the SSP scenario.[399] Each of

399 L. Clarke, K. Jiang, K. Akimoto, M. Babiker, G. Blanford, K. Fisher-Vanden, J. Hourcade, V. Krey, E. Kriegler, A. Löschel, D. McCollum, S. Paltsev, S. Rose, P. Shukla, M. Tavoni, B. van der Zwaan and D. van Vuuren, "Assessing Transformation Pathways. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change", Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA., pp. 413–510, 2014.

the SSPs is then run with varying levels of mitigation policies imposed, primarily through a price on carbon, to produce each of the global-warming scenario (RCPs). Not all pathways are able to achieve the emission reductions required for the 'high-ambition' scenario.[400]

The information provided in the SSPs are aggregated into 32 regions including individual countries Brazil, Canada, China, Indonesia, India, Japan, Republic of Korea, Mexico, Russian Federation, South Africa, Turkey and USA, and regions including the EU, sub-Saharan Africa, north Africa, Latin America, the Middle East, and other Asian countries.

The Scenario matrix architecture

The scenario matrix architecture is built by running each of the above socioeconomic pathways (SSPs) through each of the main integrated assessment models (IAMs) with varying levels of abatement rates (consisting primarily of increasingly higher carbon prices) such that they mimic the various radiative concentration pathways (RCPs). We employ each of the SSPs in this matrix but limit the warming scenarios to RCP2.6 ('high-ambition' scenario), RCP6.0 ('current policies' scenario) and RCP8.5 ('worst-case' scenario).

GDP per capita impact estimation

To provide estimates of impacts from each warming scenario on economic activity (GDP per capita) we employed modelling techniques developed by our team at the University of Oxford in collaboration with the University of Victoria, BC, in which we applied advanced econometric methods.

Using our three defined temperature scenarios, we extracted 326 CMIP5 climate models from the Earth System Grid Federation and ultimately identified 65 models that resulted in similar temperature outcomes by the end of the century (applied with a margin of ± 0.2°C).[401] For all climate model outputs, we applied a population weighting using gridded population data from 2015,[402] before aggregating the climate variables to a country level.

400 Core Writing Team, R. K. Pachauri, and L. Meyer, Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 1. Geneva, Switzerland, 2014, vol. 40]. Available: http://doi.wiley.com/10.1046/j.1365-2559.2002.1340a.x.

401 Earth System Grid Federation models. Available at: https://esgf-index1.ceda.ac.uk/. The chosen margin is added to the target temperatures to smooth climate model-specific idiosyncrasies. Changing this margin can have small effects on the reported GDP per capita impacts, but the magnitude and direction of the impacts estimated is robust to the choice of margin.

402 Doxsey-Whitfield, Erin, et al. "Taking advantage of the improved availability of census data: a first look at the gridded population of the world, version 4." Papers in Applied Geography 1.3 (2015): 226-234.

Building and expanding on the historical dataset from Pretis et al. (2018),[403] we then estimated the effect of temperature and precipitation on GDP per capita growth as well as on sectoral GDP per capita in a linear and a non-linear form in a dynamic linear panel regression with country- and time-fixed effects and including linear and squared time trends. Additionally, we used the *gets* R-package to apply Impulse Indicator Saturation (IIS) to deal with outlying observations and unmodelled shifts in the data.[404] IIS is a modelling technique which adds observation-specific dummy variables and uses general-to-specific model selection[405] to retain only indicators for previously unmodelled outliers. The target level for retention was specified at 0.1 per cent.

The subsequent outlier-robust estimated model relationship was projected to 2100 using the extracted CMIP5 models to gain insights about future climate impacts (see Table 4). The future growth effect estimates were subsequently added to the exogenously determined growth rates within the SSP scenarios and then level GDP per capita estimates were calculated. As the SSP growth rates are made in five-year intervals, values were interpolated using a spline function. We derive global and EU27 values by aggregating country-specific values using a weighted average applying SSP-specific GDP values in 2100.

Translating these country-level GDP per capita estimates to a global value is not entirely trivial and fraught with issues around how best to do this aggregation. For the main results, we present what we believe is the least biased approach but to demonstrate these aggregation issues we show three alternative aggregation methods in Table 5 that are all based on the identical set of country-level estimates. The first aggregation method, which we present in the main text, first multiplies the GDP per capita estimates that have been calculated for each temperature scenario with the country-level population values contained in the SSPs and subsequently sums the global GDP values. This total global GDP is then divided by the global sum of population to produce an aggregate global GDP per capita value. The remaining two aggregation methods are

403 Pretis, F., Schwarz, M., Tang, K., Haustein, K., & Allen, M. R. (2018). Uncertain impacts on economic growth when stabilizing global temperatures at 1.5 C or 2 C warming. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 376(2119), 20160460.

404 See Hendry, D. F., Santos, C., & Johansen, S. (2008). Automatic selection of indicators in a fully saturated regression. Computational Statistics, 23(2), 317-335. and for the R-package see Pretis, F., Reade, J. J., & Sucarrat, G. (2017). Automated general-to-specific (GETS) modelling of the mean and variance of regressions, and indicator saturation methods for outliers and structural breaks. Journal of Statistical Software.

405 Krolzig, H. M., & Hendry, D. F. (2001). Computer automation of general-to-specific model selection procedures. Journal of Economic Dynamics and Control, 25(6-7), 831-866.

simply the mean and median country-level GDP per capita impact as compared to the SSP baseline and expressed in per cent. An illustration of the significance of the choice of aggregation method can be observed in Table 5. As can be seen from these results, the uncertainty in the aggregation approach is larger than the uncertainty contained in the SSP pathways even though each SSP contains very different population and GDP levels in 2100. We chose the first aggregation method for our main results as it does not suffer the problem of using one GDP per capita number for each country (despite the enormous differences in population between countries). However, the mean and median measures are useful in that they illustrate the skewness in the distribution of outcomes for different countries, with the median levels showing a higher impact than the mean showing that the majority of countries experience significant GDP per capita declines.

TABLE 4

CLIMATE IMPACT ESTIMATION RESULTS

	DEPENDENT VARIABLE			
	GDP PER CAPITA GROWTH (01)	AGRICULTURAL GDP PER CAPITA GROWTH (02)	INDUSTRIAL GDP PER CAPITA GROWTH (03)	SERVICE GDP PER CAPITA GROWTH (04)
AR1 TERM	0.129*** (0.010)	-0.246*** (0.011)	0.058*** (0.011)	0.084*** (0.011)
TEMPERATURE	0.009*** (0.003)	2.209*** (0.561)	0.531 (0.528)	0.145 (0.332)
TEMPERATURE SQUARED	-0.0004*** (0.0001)	-0.084*** (0.016)	-0.021 (0.015)	-0.006 (0.010)
PRECIPITATION	0.0004 (0.001)	0.947*** (0.171)	0.025 (0.164)	-0.147 (0.102)
PRECIPITATION SQUARED	-0.00003 (0.00002)	-0.028*** (0.005)	-0.004 (0.005)	0.002 (0.003)
IMPULSE INDICATOR SATURATION	YES	YES	YES	YES
COUNTRY AND YEAR FE	YES	YES	YES	YES
LINEAR AND SQUARED TIME TRENDS	YES	YES	YES	YES
OBSERVATIONS	7,547	5,947	5,818	5,346
R^2	0.656	0.480	0.678	0.749
ADJUSTED R^2	0.623	0.417	0.637	0.715
RESIDUAL STD. ERROR	0.039 (DF = 6885)	7.318 (DF = 5302)	6.843 (DF = 5162)	4.170 (DF = 4706)
F STATISTIC	19.833*** (DF = 662; 6885)	7.599*** (DF = 645; 5302)	16.588*** (DF = 656; 5162)	21.916*** (DF = 640; 4706)

Note:
*p<0.1
**p<0.05
***p<0.01

TABLE 5

GLOBAL GDP PER CAPITA IMPACTS USING DIFFERENT AGGREGATION METHODS, PER CENT

SCENARIO	METHOD	SSP1	SSP2	SSP3	SSP4	SSP5
HIGH AMBITION	Global GDP per capita reduction	-27.3%	-27.2%	-25.2%	-21.4%	-25.2%
	Mean Country-Level GDP per capita reduction	-19.9%	-20.3%	-19.9%	-20.2%	-20.2%
	Median Country-Level GDP per capita reduction	-30%	-30.2%	-30%	-29.9%	-30.1%
CURRENT POLICIES	Global GDP per capita reduction	-39.9%	-39.5%	-37.1%	-31.8%	-36.8%
	Mean Country-Level GDP per capita reduction	-30.1%	-30.4%	-30.2%	-30.4%	-30.4%
	Median Country-Level GDP per capita reduction	-47.4%	-47.8%	-47.8%	-47.8%	-47.4%
WORST CASE	Global GDP per capita reduction	-45.7%	-44.9%	-42.2%	-36.9%	-42.1%
	Mean Country-Level GDP per capita reduction	-34.1%	-34.3%	-34.1%	-34.4%	-34.4%
	Median Country-Level GDP per capita reduction	-60.1%	-60.4%	-60.6%	-60.6%	-60.1%

In the main body of this report we also provide a range of estimated absolute climate impact of between USD91 trillion and USD524 trillion. The full range of estimates for absolute GDP damage are presented below in 2020 USD trillions at purchasing power parity (PPP) (Table 6). These values are calculated by multiplying the estimated GDP for each SSP by our estimated percentage global damages per capita in each SSP for each year from 2020 to 2100. This provides us with a full range of GDP damages estimates from the various socio economic scenarios. Somewhat ironically, the greater the GDP grows in a given scenario, the more that can be lost by climate change. Note that the caveats provided above on the GDP per capita estimates also apply here, suggesting these are conservative.

FIG. 21

ECONOMIC COST OF CLIMATE CHANGE, IN USD TRILLION, BY SSP SCENARIO

SCENARIO	SSP1	SSP2	SSP3	SSP4	SSP5
HIGH AMBITION	202	186	91	100	325
CURRENT POLICIES	302	272	137	149	474
WORST CASE	331	298	148	168	524

Regional GDP per capita changes

Different parts of the world will also warm at different rates in each of these three scenarios due to many factors, including latitude, the Earth's rotation, the location of land masses, and the mechanisms by which heat is dissipated around the globe via the atmosphere and oceans, with higher temperature increases generally seen in polar regions.

Impacts of warming on economic production will also vary depending on the latitude of a country with more temperate regions experiencing higher damages per degree of warming.[406] The estimates of physical damages provided in this analysis take both phenomena into account using country-specific temperature changes and damage functions.

As shown in Fig. 22, the countries in higher latitudes are estimated to experience GDP per capita increases in relation to the baseline estimate (SSP2). This includes countries with vast land masses such as Russia, Mongolia and Canada, which have already seen rapid expansion in mining and oil and gas from increased access to land,[407] and smaller European countries such as Finland, Estonia, Belarus and Latvia, where, perhaps not surprisingly, there has been a general increase in economic activity during warmer years.

406 Burke, Marshall, Solomon M Hsiang, and Edward Miguel. 2015. "Global Non-Linear Effect of Temperature on Economic Production." Nature 527(7577): 235–39.

407 Prowse, T.D., Furgal, C., Chouinard, R., Melling, H., Milburn, D., Smith, S.L. 2009. "Implications of Climate Change for Economic Development in Northern Canada: Energy, Resource, and Transportation Sectors," AMBIO: A Journal of the Human Environment 38(5), 272-281.

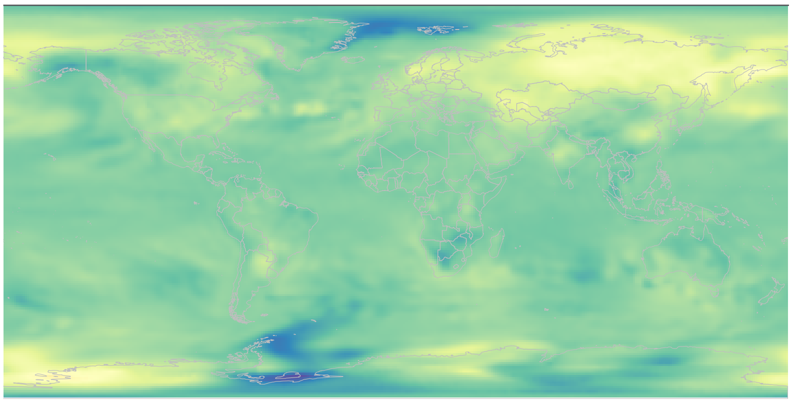
FIG.22

A GEOSPATIAL MAPPING OF THE TEMPERATURES UNDER THE THREE REFERENCE SCENARIOS

FIG.22A

2100 Global Temperature Anomaly: 1.62°C
Derived using the CMIP5 Model MPI-ESM-LR
RCP-run 2.6W/m2 - Ensemble Member r1i1p1
Colour Scale calibrated as difference to 2006

HIGH-AMBITION SCENARIO

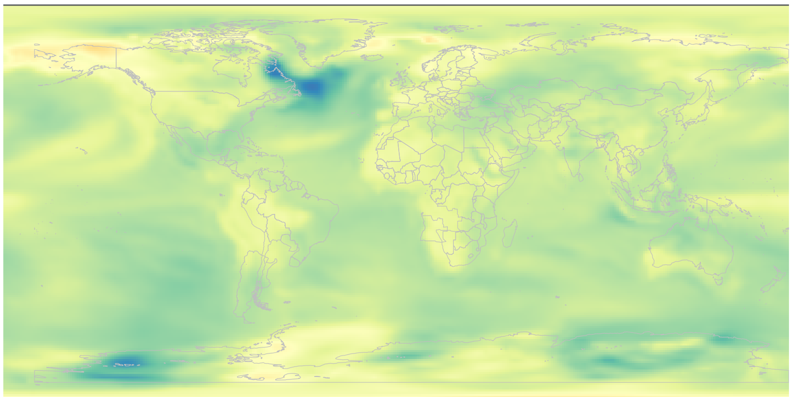


TEMPERATURE ANOMALY -5°C 0°C 5°C 10°C 15°C

FIG.22B

2100 Global Temperature Anomaly: 2.85°C
Derived using the CMIP5 Model CSIRO-Mk3-6-0
RCP-run 6.0W/m2 - Ensemble Member r2i1p1
Colour Scale calibrated as difference to 2006

CURRENT POLICIES SCENARIO

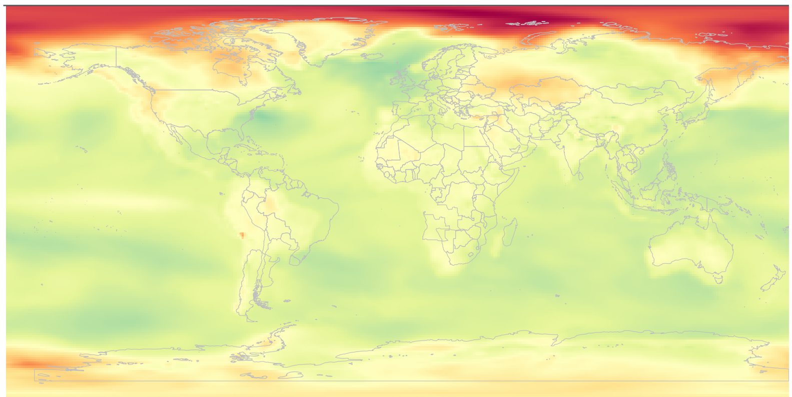


TEMPERATURE ANOMALY -5°C 0°C 5°C 10°C 15°C

FIG.22C

2100 Global Temperature Anomaly: 4.30°C
Derived using the CMIP5 Model CNRM-CM5
RCP-run 8.5W/m2 - Ensemble Member r2i1p1
Colour Scale calibrated as difference to 2006

WORST-CASE SCENARIO



TEMPERATURE ANOMALY -5°C 0°C 5°C 10°C 15°C

A number of key assumptions are required in the estimation of climate damages presented in this research. To ensure the results are as clear and transparent as possible, we have included a summary table of the methods and assumptions employed (see Table 2). There are also two key limitations we see in the methodology used to calculate the global GDP per capita impacts. The impact estimates are based on year-to-year differences that have occurred in the past and their impact on GDP in various latitudes.[408] Extrapolating such empirical changes to temperatures that will occur in the future and are likely outside the range of observations is obviously problematic. Various natural and anthropogenic phenomena will have temperature thresholds beyond which costs outweigh the benefits – which is why global warming affects the already warmer temperate regions so profoundly. Also, this method is only valid when looking at individual countries in isolation i.e. assuming that the higher latitude countries are not dragged down by the economic declines in the rest of the world. This would include, for example, the impacts that reductions in GDP per capita in the US might have on the economic growth of their trading partners. Such feedback effects will be country-specific and will depend on the type of goods that are imported and exported and the performance of the economies with which each country trades. We explore these potential feedbacks on three of the key emerging economies, Russia, China and India, which provide a reasonable range of potential outcomes.

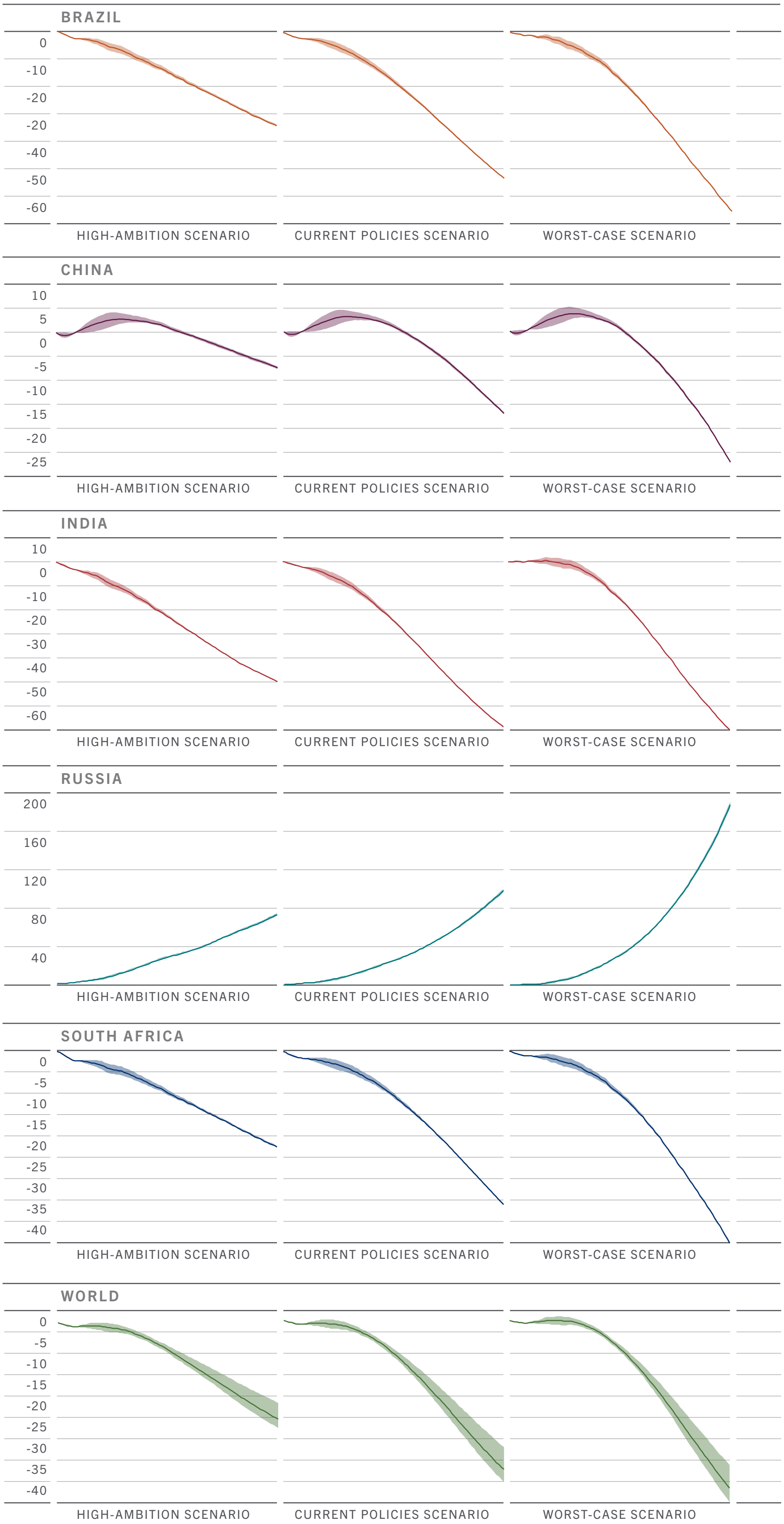
The country-level impacts estimated using this methodology are probably most controversial for Russia, which, using our methodology, has significant gains in GDP per capita in all three scenarios (Figure 22). As mentioned previously, these result from our data-driven approach – warming has increased the GDP of countries at high latitudes in the past. However, projecting forwards, our approach very likely leads to an over-estimate of the benefits for Russia. Further, Russia is not an island and its economic performance is a function of the success of its trading partners, and most of the world is expected to experience negative impacts to their economic growth from climate change. The adjustment required to results here, were such global trade impacts taken into account, would depend on the climate scenario, the sectors that dominate Russia's trade in the future, and the extent to which Russia adapts to the changing circumstances. In 2018 half of Russia's exports were fossil fuel-based.[409] Unless Russia can diversify away from these commodities in the 'high-ambition' scenario, Russia's exports, and hence domestic economic growth, are likely to decline.

408 Ibid.
409 Mineral fuels, oils and waxes accounted for 50.4% of exports in 2018 - United Nations. "UN Comtrade: International Trade Statistics." https://comtrade.un.org/data/ (8 August 2018).

Weighted average of SSP-specific 2100 GDP weights. Global value is the global GDP per capita (sum of global GDP/sum of global population) compared to baseline.

FIG.23

ESTIMATED CLIMATE CHANGE DAMAGE UNDER THE THREE WARMING SCENARIOS, MEAN, MIN AND MAX GDP PER CAPITA COMPARED TO NO CLIMATE CHANGE, % SHORTFALL (2011-2100)



Source: this report

The impact on Russia's exports in the less ambitious scenarios would be mixed and hence more difficult to predict, particularly given recent trends towards more tightly integrated global supply chains.[410] As decarbonisation occurs more slowly in the less ambitious scenarios, Russia is likely to benefit from the continued global demand for its fossil fuel exports. However, as direct climate change impacts reduce economic growth for most countries beyond 2050, including major trading partners such as China, there is likely to be a fall in demand for some of Russia's exports. Russia experienced a 7.8 per cent decline in GDP in 2009[411] during the global financial crisis despite minimal exposure to the sub-prime mortgage assets or failed institutions that initiated the crisis. If, despite this, Russia's economy does grow faster than other countries', as predicted in this study, the real exchange-rate effects could also adversely affect Russia's exports.[412] On the other hand, a global downturn could conceivably result in a decline in oil and gas prices, as happened during the Covid-19 pandemic (although historically the relationship appears mixed);[413] this could increase Russia's oil and gas exports due to increased demand from importing economies taking advantage of the lower prices.[414]

The economic impact on China of a climate change-induced global economic downturn is perhaps clearer. China has had positive terms of trade with the rest of the world for a number of decades, supplying 20 per cent or more of the world's exports of textiles, electronics and machinery.[415] With this state of affairs likely to persist, China would experience an increased economic contraction from any decline in the global economy associated with climate change, as happened during the 2008 global financial crisis.[416] As China has been a net importer of oil since 1996,[417] with some 9 per cent of its current USD2 trillion in imports in petroleum oils, coal and gas,[418] it is likely to receive a

410 Subbarao, D., 2009, Impact of the Global Financial Crisis on India, Collateral Damage and Response, Speech delivered at the Symposium on "The Global Economic Crisis and Challenges for the Asian Economy in a Changing World" organised by the Institute for International Monetary Affairs, Tokyo on 18 February 2009, https://rbidocs.rbi.org.in/rdocs/Speeches/PDFs/Speech%20-%20as%20sent-%20Modified%20_4_.pdf

411 MacroTrends data, Accessed 26/7/2020, http://www.macrotrends.net/countries/RUS/russia/gdp-gross-domestic-product

412 Le, Thai Ha, and Youngho Chang. 2013. "Oil Price Shocks and Trade Imbalances." Energy Economics 36: 78–96.

413 Rafiq, Shudhasattwa, Pasquale Sgro, and Nicholas Apergis. 2016. "Asymmetric Oil Shocks and External Balances of Major Oil-Exporting and Importing Countries." Energy Economics 56: 42–50. http://www.sciencedirect.com/science/article/pii/S0140988316300342.

414 Charnavoki, Valery, and Juan J. Dolado. 2014. "The Effects of Global Shocks on Small Commodity-Exporting Economies: Lessons from Canada." American Economic Journal: Macroeconomics 6(2): 207–37.

415 United Nations. "UN Comtrade: International Trade Statistics." https://comtrade.un.org/data/ (August 8, 2018).

416 Morrison, W.M., 2009, China and the Global Financial Crisis: Implications for the United States, Congressional Research Services, https://apps.dtic.mil/sti/pdfs/ADA501432.pdf

417 Wu, G., Zhang, Y, 2014, Does China factor matter? An econometric analysis of international crude oil prices,

Energy Policy, Volume 72, https://doi.org/10.1016/j.enpol.2014.04.026

418 United Nations. "UN Comtrade: International Trade Statistics." https://comtrade.un.org/data/ (8 August 2018).

small boost from any decline in oil prices,[419] but this is unlikely to compensate for the decline in export earnings.

China's trade balance would probably fare best in the 'high-ambition' scenario as much of the additional renewable generation capacity required for this scenario is likely to be produced there. Incorporating more renewables in China's own domestic generation capacity would also reduce reliance on energy imports, improving their terms of trade still further.

The impacts of a global slowdown on India's economy would be difficult to predict, although it seems unlikely that it would experience an economic boost. Much of India's economic growth over recent years has been driven by domestic consumption and investment,[420] with India's exports representing only 15 per cent of its GDP – it has been a net importer during recent decades.[421] However, despite this reliance on domestic markets India still experienced a contraction of its economy during the 2008 financial crisis, even with no direct exposure to the key assets and institutions involved in this crash.[422] The decline in 2008 was attributed instead to its export market exposure and heavy dependence on foreign investment, which fell prey to the global liquidity freeze.[423] Also, India has a large underground or black economy, estimated at 50 per cent of GDP, including enormous illicit outflows of assets to foreign ownership, which increased during the financial crisis, adding to its impact.[424]

India's economy could experience gains in the 'high-ambition' scenario, but it does not seem likely that it would fare as well as China. Its capacity for producing new clean technologies is somewhat hampered by labour laws that favour incumbent industries,[425] making it less able to capitalise on any boom in renewables. However, as India is a net importer of fossil fuel products, it would probably gain from increased reliance on increasingly cheaper renewable capacity given the country's potential domestic renewable resources.[426]

419 Li, K., Fang, L., He, L., 2020, The impact of energy price on CO_2 emissions in China: A spatial econometric analysis, Science of The Total Environment, Volume 706, https://doi.org/10.1016/j.scitotenv.2019.135942

420 United Nations. "UN Comtrade: International Trade Statistics." https://comtrade.un.org/data/ (8 August 2018).

421 Ibid.

422 Subbarao, D., 2009, Impact of the Global Financial Crisis on India, Collateral Damage and Response, Speech delivered at the Symposium on "The Global Economic Crisis and Challenges for the Asian Economy in a Changing World" organised by the Institute for International Monetary Affairs, Tokyo on 8 February 2009, https://rbidocs.rbi.org.in/rdocs/Speeches/PDFs/Speech%20-%20as%20sent-%20Modified%20_4_.pdf

423 Ibid.

424 Kar, D., 2010, "The Drivers and Dynamics of Illicit Financial Flows from India: 1948-2008", Global Financial Integrity, Accessed 9 July 2020, http://www.gfintegrity.org/wp-content/uploads/2014/02/GFI_India.pdf

425 Kochhar, K., Kumar, U., Rajan, R., Subramanian, A., Tokatlidis, I., 2006, India's pattern of development: What happened, what follows?, Journal of Monetary Economics, Volume 53, Issue 5

426 State-led studies have estimated Indian solar potential installed resource at 750 GW, onshore wind at 302 GW and hydro at 149 GQ, which is over 3 times current electricity demand ["National Electricity Plan (NEP) Volume 1 Generation.," Central Electricity Authority, Ministry of Power, Government of India, Jan 2018; "Year-End Review 2018 – MNRE," Press Information Bureau: Government of India: Ministry of New and Renewable Energy, 8 December 2018; "Hydro Power Development Report," Central Electricity Authority, Ministry of Power, India, 2018.]

Ultimately, the magnitude of the estimated impacts provided in this report should be considered with caution, as uncertainties remain high and precision low. Furthermore, the credibility of the results declines the further the temperatures increase beyond current experience so our confidence will be lowest in the 'worst-case' scenario estimates. However, the overall country-specific direction of this effect, in economic isolation, appears to be quite robust to model specification. Further research would be needed to fully incorporate the interactions of individual countries in a global economic model where trade feedback dynamics were included.

Biodiversity changes

The estimated changes in biodiversity for each warming scenario are based on an application of the GLOBIO4 model,[427] which approximates the impact of climate change on Mean Species Abundance (MSA) as a function of multiple anthropogenic pressures on the environment.[428] The MSA provides a measure of the abundance of species associated with a pristine habitat, which can be translated into a measure of square kilometres of pristine habitat lost. The MSA is applied to a subset of SSPs against the three warming scenarios based on the biodiversity model inter-comparison protocol of Kim et al. (2018).[429] The 'high-ambition' scenario (RCP2.6) is linked with the 'sustainability' pathway (SSP1), which involves low land-use pressure, while the 'current policies' scenario (RCP6.0) is linked with the 'regional rivalry' pathway (SSP3), which involves high land-use pressure, and the 'worst-case' scenario (RCP8.5) is linked with the 'fossil-fuelled development' pathway (SSP5), which has moderate land-use pressure. The latter two combinations represent fairly low mitigation and environmental sustainability efforts. The 'high-ambition' + 'sustainability' (RCP2.6 + SSP1) combination includes both ambitious mitigation measures and significant land-use changes including reforestation and bioenergy production.

427 Schipper, Aafke M. et al. 2020. "Projecting Terrestrial Biodiversity Intactness with GLOBIO 4." Global Change Biology 26(2): 760–71.

428 Alkemade, R., van Oorschot, M., Miles, L., Nellemann, C., Bakkenes, M. and ten Brink, B. 2009, 'GLOBIO3: A Framework to Investigate Options for Reducing Global Terrestrial Biodiversity Loss', Ecosystems 12:374-390

429 Kim, H., et al. 2018. A protocol for an intercomparison of biodiversity and ecosystem services models using harmonized land-use and climate scenarios, Geosci. Model Dev., 11, 4537–4562, https://doi.org/10.5194/gmd-11-4537-2018.

Transition risks

The estimates provided for the transition risk associated with stranded assets in the 'high-ambition' scenario are based on the recent work of Tong et al. (2019).[430] The calculations of committed emissions are detailed in Tong et al. (2019), but some key components are included below for reference.

The evaluation of energy infrastructure in Tong et al. is an update on the work of Pfeiffer et al. (2018), including greater spatial disaggregation and the removal of pipeline infrastructure that has been cancelled since Pfeiffer et al. was published. Electricity infrastructure includes the main activity of electricity and heat production, petroleum refining as well as the manufacturing of solid fuels, and other energy industries. The estimated lifetime of all electricity-generating units is set to 40 years, including those owned by large industrial and commercial industries. Emissions from agriculture, forestry, fishing and aquaculture are included under 'Other energy.'

The quantification of industrial emissions is a valuable improvement over past efforts including detailed data collected on Chinese infrastructure. Iron/steel and non-metallic minerals (for example, cement and glass) industries account for about 50 per cent of all industrial CO_2 emissions in recent years, and China produces about 50 per cent of the world's raw steel and 57.3 per cent of the world's cement.

Transportation emissions in Tong et al. are also an important addition and include road transport, other transport and international transport. Road emissions are based on an extensive database of motor vehicle numbers, classes, fuel type and vintages from 40 major countries and regions. Other transportation includes aviation, rail, pipeline, and navigation.

It should be noted that Tong et al. findings are somewhat contrary to another recent study by Smith et al. (2019)[431], which argues with aggressive mitigation of non-CO_2 forcing the 1.5 degrees target is still achievable with current energy infrastructure.

The range of USD5 trillion to USD17 trillion in asset valuation at risk represents the range of possible stranded asset value estimated by Tong et al. (2019).[432] The minimum represents the minimum value of assets that would have to

430 Tong, Dan et al. 2019. "Committed Emissions from Existing Energy Infrastructure Jeopardize 1.5 °C Climate Target." Nature 572(7769): 373–77.

431 Smith, Christopher J., Allen, M., et al. 2019. "Current Fossil Fuel Infrastructure Does Not yet Commit Us to 1.5 °C Warming." Nature Communications 10(1): 1–10.

432 From Fig. 4 and the point where the total committed emissions exceed approximately 420 Gt CO_2, which is the carbon budget remaining in 2018 that gives the world 66% chance of meeting the 1.5 degrees goal based on Peters, Glen P. 2018. "Beyond Carbon Budgets." Nature Geoscience 11(6): 378–80 and Schurer, A P et al. 2018. "Interpretations of the Paris Climate Target." Nature Geoscience: 1–2. https://doi.org/10.1038/s41561-018-0086-8 (March 21, 2020).

be stranded to have a 50 per cent chance of limiting warming to 1.5 degrees (580 Gt CO_2). The maximum asset risk results from stranding all the assets with the highest asset value per committed emissions (primarily in transport) to give a 66 per cent chance of limiting warming to 1.5 degrees (420 Gt CO_2). It could be argued that it is less likely that such higher value assets will be stranded; however some stranding or early retirement of transport assets is likely given the growing numbers of towns, cities and states that are requiring zero carbon transport in the coming decades and required to meet ambitious transition pathways.[433]

Sea-level rise

During the 20th century, global sea level (GSL) rose by nearly 20 cm (e.g. Dangendorf et al. 2017). While this may not appear much, the rise itself has not been linear. Recent work indicates that 7 cm of GSL rise occurred from 1990 to present-day (Nerem et al. 2018). Different observational and modelling approaches arrive at a similar conclusion that GSL change is in fact accelerating (e.g. Dangendorf et al. 2017, 2019, Nerem et al. 2018, Slangen et al. 2017) or at the very least rising faster today than at any time in the common era (e.g. Kopp et al. 2016, IPCC SROCC 2019).

Long-term global sea-level change is a response of multiple Earth system components (Fig. 23) to the imbalance in Earth's energy budget. Each of these components changes by different magnitudes, over different timescales. The main three are, thermal expansion of the ocean due to the absorption of solar radiation, glaciers and ice sheet in Greenland and Antarctica melting due to increasing atmospheric and ocean temperatures. In addition, man-made influences on the hydrological system (freshwater impoundment, groundwater pumping) also have a detectable GSL effect.

In addition to GSL change, each of the components has its own, unique global pattern that changes in time and space. The patterns occurring from water or ice loss on land are due to changes in Earth's gravitational field induced by the transfer of mass from one place to another

433 IEA (2017), Energy Technology Perspectives 2017, IEA, Paris https://www.iea.org/reports/energy-technology-perspectives-2017

(e.g. Mitrovica et al. 2001,[434] Bamber & Riva, 2009[435]). The patterns due to the warming ocean are due to the non-uniform exposure of the ocean surface to solar radiation (the energy imbalance is higher in the tropics), which redistributes ocean mass, thus inducing a gravitational field adjustment and hence a regional sea-level change (e.g. Richter et al. 2013[436]). Additional sea-level effects occur regionally: ocean currents driven by wind and heat transport, and vertical land motion that responds to ice-losses since the last deglaciation, plate tectonics, groundwater extraction and sediment compaction. These last two effects are particularly significant for large coastal cities situated on river deltas – the result being subsidence that occurs at rates sometimes more than double that of oceanic sea-level rise.[437]

The reasonably complete understanding of the mechanisms driving global and regional sea-level change, combined with large-scale climate modelling experiments under different emissions scenarios has allowed the research community to produce global and regional sea-level projections for a consistent set of emissions scenarios resulting in end-of-century radiative forcing of 2.6, 4.5, 6.0 and 8.5 W/m^2.[438] IPCC Assessment and Special Reports[439,440,441] have assessed the academic literature resulting in median and likely range (17-84th percentile) GSL projections presented in Table 7.

434 Mitrovica, J.X., Tamisiea, M.E., Davis, J.L. and Milne, G.A., 2001. Recent mass balance of polar ice sheets inferred from patterns of global sea-level change. Nature, 409(6823), pp.1026-1029.

435 Bamber, J. and Riva, R.E.M., 2010. The sea-level fingerprint of recent ice mass fluxes. The Cryosphere, 4 (4), 2010.

436 Richter, K., Riva, R.E.M. and Drange, H., 2013. Impact of self-attraction and loading effects induced by shelf mass loading on projected regional sea-level rise. Geophysical research letters, 40(6), pp.1144-1148.

437 Deltares Taskforce Subsidence., 2015. Sinking cities: an integrated approach towards solutions. http://publications.deltares.nl/Deltares142.pdf (Deltares, Delft/Utrecht).

438 Moss, R.H., Edmonds, J.A., Hibbard, K.A., Manning, M.R., Rose, S.K., Van Vuuren, D.P., Carter, T.R., Emori, S., Kainuma, M., Kram, T. and Meehl, G.A., 2010. The next generation of scenarios for climate change research and assessment. Nature, 463(7282), pp.747-756.

439 Allen, et al., 2018: Framing and Context. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. In Press.

440 Oppenheimer, et al., 2019: Sea-Level Rise and Implications for Low-Lying Islands, Coasts and Communities. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. In press.

441 Church, et al., 2013: Sea-Level Change. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, et al. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

TABLE 7

MEDIAN AND LIKELY RANGE (ITALICS) OF GSL PROJECTIONS UNDER EMISSIONS AND TEMPERATURE SCENARIOS PUBLISHED BY IPCC. ALL VALUES ARE IN METRES RELATIVE TO THE PERIOD 1986-2005. THERE HAS BEEN APPROXIMATELY 0.074 ± 0.010 M GSL SINCE 1995

YEAR	IPCC AR5 (2013)				IPCC SR1.5 (2018)*		IPCC SROCC (2019)		
	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5	1.5 °C	2.0 °C	RCP 2.6	RCP 4.5/6.0	RCP 8.5
2050	0.24 *0.19-0.32*	0.26 *0.19-0.33*	0.25 *0.18-0.32*	0.30 *0.22-0.38*			0.24 *0.17-0.32*	0.26 *0.19-0.34*	*0.32* *0.23-0.40*
2100	0.44 *0.28-0.61*	0.53 *0.36-0.71*	0.55 *0.38-0.73*	0.74 *0.52-0.98*	- *0.20-0.80*	- *0.30-1.00*	0.43 *0.29-0.59*	0.55 *0.39-0.72*	0.84 *0.61-1.10*

Source: *IPCC SR1.5 (2018) mid-point of reference period, Nerem et al. 2018

In the near term (next 30 years), median GSL across all scenarios ranges from 0.24 to 0.32 m, with a likely range of 0.19 to 0.40 m. Divergence between scenarios occurs in the latter half of the century, leading to median GSL of 0.43 m under RCP 2.6 to 0.84 m under RCP 8.5. Changes in projected GSL between IPCC assessments for the same scenario show minimal differences (1.5 and 2.0 °C for IPCC SR1.5 [2018] are within the family of RCP 2.6/ 4.5/6.0 scenarios) for both median and likely range, with the exception of RCP 8.5 in IPCC SROCC (2019) where recent modelling indicates a 0.1 m increase in the contribution from Antarctica.

Given the long-term response of sea level to forcing, the difference in projected GSL between RCP 4.5 and RCP 6.0 is unsurprisingly very small over the 21st century. Only when projections extend to 2300 does divergence between these two scenarios occur and remains relatively small.[442]

From a regional perspective, RSL projections deviate from the global average by up to ±20 per cent,[443] due to the individual patterns associated with each sea level component mentioned earlier. The relative contributions of each component will also influence the extent to which coastlines experience an amplified sea-level change (greater than GSL) or reduced sea-level change. Fig. 4 shows the pattern of median RSL, including glacio-isostatic adjustment (long wavelength vertical land motion), for RCP 2.6, 4.5/6.0 and 8.5 in 2050 and 2100.[444] Patterns of coastal sea-level change are similar between scenarios and while their magnitude is similar in 2050, they deviate after this point to 2100.

442 Kopp, R.E., et al., 2014. Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites. Earth's future, 2(8), pp.383-406.

443 Jackson, L.P. and Jevrejeva, S., 2016. A probabilistic approach to 21st century regional sea-level projections using RCP and High-end scenarios. Global and Planetary Change, 146, pp.179-189.

444 Ibid.

The likely range used by IPCC reflects the degree of certainty regarding future changes in the Earth system. For future sea-level change, these uncertainties overlap between scenarios and, it should be noted, only represent 66 per cent of possible sea level responses. Furthermore, one key mechanism remains enigmatic in the modelling of future sea-level: the dynamic response of the Greenland and especially Antarctic ice sheets. Considerable debate has occurred, drawing on rarely seen mechanisms in Antarctica becoming commonplace (ice-cliff instability),[445] expert elicitation (e.g. Bamber et al. 2019),[446] statistical modelling, and of course conventional process modelling improvements (e.g. Golledge et al. 2019).[447] This has resulted in a range of low probability (95th percentile is typically used in the literature), high-impact future sea-level rises under high emissions scenarios, in particular RCP 8.5, ranging from 1.27 m to more than 2 m (e.g. Vega-Westhoff et al. 2020).[448]

While long-term sea-level change will have a coastal impact through inundation, it is the effect it has upon changing extreme sea levels that warrants greater concern for developed and developing nations alike. Extreme sea level is the sum of tides, wind-driven waves, storm surges and mean sea level (e.g. Vousdoukas et al. 2018).[449] Thus, altering the long-term mean sea level alters the baseline upon which these short-term events occur. Not only that, but the frequency of a present-day water level for a one-in-100 year storm surge will change, making such a water level occur more often. Under RCP 8.5 it has been estimated that present-day one-in-100 year flood events will occur annually in the tropics by mid-century, and globally by 2100 primarily due to long-term mean-sea level rise (Vousdoukas et al. 2018).

445 DeConto, R.M. and Pollard, D., 2016. Contribution of Antarctica to past and future sea-level rise. Nature, 531(7596), pp.591-597.

446 Bamber, J.L., Oppenheimer, M., Kopp, R.E., Aspinall, W.P. and Cooke, R.M., 2019. Ice sheet contributions to future sea-level rise from structured expert judgment. Proceedings of the National Academy of Sciences, 116(23), pp.11195-11200.

447 Golledge, et al., 2019. Global environmental consequences of twenty-first-century ice-sheet melt. Nature, 566(7742), pp.65-72.

448 Vega- Westhoff, B., Sriver, R.L., Hartin, C., Wong, T.E. and Keller, K., 2020. The Role of Climate Sensitivity in Upper-Tail Sea-Level Rise Projections. Geophysical Research Letters, 47(6), p.e2019GL085792.

449 Vousdoukas, M.I., Mentaschi, L., Voukouvalas, E., Verlaan, M., Jevrejeva, S., Jackson, L.P. and Feyen, L., 2018. Global probabilistic projections of extreme sea levels show intensification of coastal flood hazard. Nature communications, 9(1), pp.1-12.

Coastal damages

Coastal damages are typically assessed by analysing the magnitude and frequency of the hazard, the degree of exposure, and the level of resilience. These three factors contribute to the overall risk.

For the analysis associated with this report, we particularly focus upon the extreme sea-level components of mean sea-level change and storm surge for the hazard, which dominate in most coastal settings (high-tide flooding is becoming problematic given rising RSL in, for example, Miami,[450] but these are at present mainly a nuisance rather than a single high-cost event). Exposure is defined by the population-elevation distribution within a city scaled by a global factor to account for infrastructure assets. Resilience is defined by pre-existing coastal defence levels quantified as the maximum present-day water-level return period they are capable of handling. We utilise a coastal damage model by Hallegatte et al. (2013)[451] that models exposure of 136 coastal cities worldwide for a range of global sea-level rises, local storm-surge water levels and local subsidence, where appropriate (cities located within major river deltas have their RSL projections adjusted by -2 mm yr-1; Ericson et al. 2006).[452] We adapt the model to use median RSL projections for RCP 2.6, 4.5/6.0 and 8.5 from Jackson & Jevrejeva (2016)[453] and Jackson et al. (2018),[454] which are in line with recent IPCC published estimates (Table 7). As mentioned before, GSL pathways under RCP 4.5 and RCP 6.0 scenarios are effectively the same over the 21st century, hence our use of the former. In addition, to provide projections in line with those estimates by IPCC SROCC (2019), we use the high-end scenario described in Jackson & Jevrejeva (2016), which includes a larger contribution to sea level from Antarctica but is tied to RCP 8.5 in terms of its emissions scenario. Population trajectories

450 Wdowinski, S., Bray, R., Kirtman, B.P. and Wu, Z., 2016. Increasing flooding hazard in coastal communities due to rising sea level: Case study of Miami Beach, Florida. Ocean & Coastal Management, 126, pp.1-8.

451 Hallegatte, S., Green, C., Nicholls, R.J. and Corfee-Morlot, J., 2013. Future flood losses in major coastal cities. Nature climate change, 3(9), pp.802-806.

452 Ericson, J.P., Vörösmarty, C.J., Dingman, S.L., Ward, L.G. and Meybeck, M., 2006. Effective sea-level rise and deltas: causes of change and human dimension implications. Global and Planetary Change, 50(1-2), pp.63-82.

453 Jackson, L.P. and Jevrejeva, S., 2016. A probabilistic approach to 21st century regional sea-level projections using RCP and High-end scenarios. Global and Planetary Change, 146, pp.179-189.

454 Jackson, L.P., Grinsted, A. and Jevrejeva, S., 2018. 21st Century Sea-Level Rise in Line with the Paris Accord. Earth's Future, 6(2), pp.213-229.

are those used in Hallegatte et al. (2013),[455] which use the OECD ENV-linkages model[456] where OECD regional population projections are downscaled to city levels based on their country's current development status. We follow Hallegatte et al. (2013)[457] by using a population cap of 35 million people within a given city limit.

We present the top sixteen projected annual average losses (AAL) in 2030, 2050 and 2100 for each city under an adaptation scenario where only present-day protection heights are maintained and overtopping of defences by a storm surge results in complete inundation of elevations up to that water level (Table 8). These experiments are performed for median RSL projections of the three emission scenarios.

455 Hallegatte, S., Green, C., Nicholls, R.J. and Corfee-Morlot, J., 2013. Future flood losses in major coastal cities. Nature climate change, 3(9), pp.802-806.
456 OECD, 2012. OECD Environmental Outlook to 2050: The Consequences of Inaction. OECD Publishing: Paris.
457 Hallegatte, S., Green, C., Nicholls, R.J. and Corfee-Morlot, J., 2013. Future flood losses in major coastal cities. Nature climate change, 3(9), pp.802-806.

APPENDIX

TABLE 8

AVERAGE ANNUAL LOSSES (MILLIONS 2005 USD) FOR COASTAL CITIES DUE TO PRESENT-DAY 1-IN-100 YEAR FLOOD EVENT COMBINED WITH MEDIAN RSL PROJECTIONS UNDER RCP SCENARIOS

		AAL MILLIONS USD (2005)								
		RCP2.6			RCP4.5/6.0			RCP8.5*		
CITY	COUNTRY	2030	2050	2100	2030	2050	2100	2030	2050	2100
MIAMI	USA	7,696	21,943	222,125	7,229	21,943	366,528	7,696	34,011	1,569,008
NEW YORK	USA	7,040	30,350	509,904	7,040	30,350	955,467	8,095	53,037	1,146,391
SHANGHAI [D]	China	1,131	17,843	854,524	1,218	22,323	930,397	1,313	40,565	1,072,319
GUANGZHOU GUANGDONG [D]	China	105,868	256,416	842,491	106,144	258,042	867,176	106,422	261,628	936,578
BANGKOK [D]	Thailand	3,540	50,616	602,855	3,755	60,451	686,069	3,984	87,104	916,625
CALCUTTA [D]	India	11,269	135,895	616,063	11,961	137,382	661,061	13,476	141,751	797,542
MUMBAI	India	10,835	68,595	637,107	9,389	79,163	659,010	12,505	161,393	719,397
NEW ORLEANS [D]	USA	23,629	243,310	668,186	19,980	242,388	672,467	23,629	246,067	704,221
OSAKA-KOBE [D]	Japan	35,131	195,736	513,365	40,471	200,682	541,083	46,624	210,997	627,686
TOKYO [D]	Japan	10,897	162,948	450,530	12,641	169,342	484,738	17,010	181,449	599,268
HO CHI MINH CITY [D]	Vietnam	1,551	9,286	148,591	1,589	9,742	228,655	1,667	11,799	554,574
GUAYAQUIL [D]	Ecuador	7,466	34,029	397,612	7,503	34,295	411,591	7,541	35,047	485,165
TIANJIN [D]	China	17,407	74,406	302,086	17,407	76,150	323,744	20,547	80,517	380,692
VIRGINIA BEACH	USA	1,625	7,306	155,829	1,493	7,953	270,857	1,769	14,410	335,123
HONG KONG	China	255	1,336	39,314	255	1,491	132,242	284	2,890	332,673
ALEXANDRIA [D]	Egypt	8,315	42,385	271,374	8,315	42,617	285,116	11,030	44,486	326,225

*refers to the use of the median High-end scenario (Jackson & Jevrejeva, 2016), which is based upon RCP 8.5 except for additional ice-sheet mass loss.
[D] refers to a city located on a river delta, and thus includes subsidence (see Hallegatte et al. 2013

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Issued in November 2020