Flatten-the-curve: Why total carbon emissions matter much more than 'date of zero'

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Executive Summary

The recent Intergovernmental Panel on Climate Change (IPCC) report on climate change painted a dire picture of global warming, especially climate shifts and variance across countries. It highlights the need to limit emissions, and if the ambition is to keep warming under 1.5° Celsius, the summary is the world needs to get to zero by 2050.

A number of countries have announced plans to reach "net-zero" by 2050 or thereabouts. There are several problems with these announcements. First, are these really zero, or 'net' through futuristic or unfair offsets or, even worse, accounting tricks? Offsets are unfair when they are based on 'all carbon is equal' even though *abating* carbon isn't equal in cost. 'Economic efficiency' has a skew that favours high-emitters, who benefit from offsets out of low-emitters (poorer countries) with early-in-the-trajectory abatement. Second, even if one does reach zero, what is the shape of the trajectory to get there? Most countries are conspicuously quiet on the details. The shape would determine the cumulative emissions over time, which is what really matters. Third, are all countries expected to reach the target at roughly the same time? Not only is this unfair to low-emitters (who are invariably poorer, developing countries), coming to zero by 2050 would still mean many high-emitters would still emit well more than their "fair share" of emissions through most apportionments of a global carbon budget. This is after being generous and writing off all historical emissions, even though carbon dioxide lingers in the atmosphere for centuries.

Becoming zero is important, but "date of net-zero" is incomplete, lacking any measure of what the date *should* be. "Sooner is better" remains a motherhood statement. To address many of these issues, this paper presents a richer framework for both creating a yardstick for cross-country comparison as well as incentivizing countries to lower their cumulative emissions going forward. This yardstick is, by design, based on total emissions. It thus overcomes the limitations of the 'date of zero' approach, which ignores any front-loading of emissions. The area-under-the-curve approach, which also tells us the date of zero, is richer because it directly indicates if a country is behind schedule and likely to bust its budget. It also tells us how much time a country with low emissions has before it must peak emissions.

The framework uses a standardized trajectory for all countries that assumes they need time, nominally 30 years, to reach zero. Low emitters also have some remaining carbon space so they can continue as-is for "N" years until they have to peak and still stay in budget. High emitters may not even have 30 years to linearly decline to zero and stay in budget. They solve for a negative "N", meaning they should have begun their decline in the past to allow themselves 30 years to come to zero, or they must decline faster to stay in budget. To reach zero in thirty years (a 2050 target) means a country has no years left before the 30-year decline to zero ("N" = 0).

Growth in emissions from low emitters for a few years is inevitable and embedded in the framework. In 2019, the countries with per capita fossil CO_2 emissions below the world average, with 60% of the world's population, had only 22% of global fossil CO_2 emissions. A billion people in sub-Saharan Africa (excluding South Africa) were responsible for only 1% of global emissions. Any model expecting them to immediately focus on "zero emissions" is naïve and discriminatory.

Importantly, this framework enables a system that incentivizes low emissions countries to "flatten the curve" – to peak emissions later, but lower. This would enable them to have a combination of lower cumulative emissions or the same emissions at a lower cost (given low-carbon technologies are getting cheaper over time). Net-zero by a rigid date wouldn't support this. It would also fail to push for any low-hanging fruit of early emissions reduction, which could give some countries limited carbon space to let small residual emissions continue for a few years.

If the world does bust its carbon budget, it will be because of a subset of high-emission countries. These countries should make global finance transfers that enable low emitters to flatten their curve. They should also pay down costs along the learning curve for abatement technologies, such as green hydrogen, carbon capture, etc., that are currently expensive. However, for most high-emission countries, relying on direct air carbon capture to stay within an appropriate carbon budget as per this framework will not be practical due to the scale involved. In some cases, they would need to remove 50 percent to 275 percent of current emissions annually. This is before considering the high cost of such solutions. These points emphasise that countries should first focus on decreasing emissions.

This paper also shows that carbon pricing, currently based on incremental emissions per ton, may not be directly compatible with a framework focused on cumulative emissions. It is also unclear if pricing alone will lead to sufficient reductions. When we consider issues of equity, the situation is unfair to poorer (low-emission) countries, whose emissions will only grow. Any framework with rising carbon prices is especially unfair.

Given we do need to get to zero globally, countries need to articulate their trajectories for achieving their targets. Offsets should be considered with strong caution, and with separate accounting. As this framework shows, the shape of the trajectory is very important, which ultimately determines the cumulative emissions (the area-under-the-curve). All countries should focus on any low-hanging fruit of early reductions, which for high emitters will become absolute reductions and for low emitters represent a reduction in emissions growth rate.

Introduction: Climate Change is more than a technical challenge

US Special Presidential Envoy John Kerry called the upcoming COP26 in Glasgow "the last, best opportunity that we have" to address climate change. While this call to action is welcome, there is increased scrutiny upon developing regions to step up their ambitions for reducing emissions. Recently, a number of regions or countries have announced net zero emissions targets, often for 2050. China announced a plan on 22nd September 2020 to become 'climate neutral' (colloquially equivalent to "net-zero" emissions) by 2060,[1] and all eyes are on India to make a similar net-zero announcement.[2]

[1] The literal translation is "to strive to", but all indications suggest government agencies are treating this as a firm target.

[2] Opinions by Navroz Dubash (2021), Thomas Spencer (interviewed by Akshat Rathi (2020)), and Jayant Sinha (2021) present a range of views on India's possible net-zero pledge. Some of them are circumspect while others are enthusiastic.

However, is a net-zero target appropriate for developing regions that are historically low emitters? This paper focuses on differences in emissions between countries and presents a more appropriate framework for comparisons than one based simply on the announced date of net-zero.

While climate change is a complex technical issue with variations across regions and timeframes, how we approach the problem and attempt to address it is a policy or political construct. Nonetheless, there are a few fundamentals that impact the policy space available.

Anthropogenic emissions of greenhouse gases (GHG), of which the largest is carbon dioxide (CO2), directly contribute to climate change. CO2 has a very long life in the atmosphere and cumulative emissions are thus the key marker for causality. On the flip side, unfortunately, even if CO2 emissions were to peak, atmospheric concentrations would continue to rise. This is one reason global consensus is moving towards the need to achieve zero emissions, and this was the recent IPCC (2021) report's key message, as part of Assessment Review VI.[3]

A simplified framework for climate change boils down to five fundamental issues:

1) *Carbon space* – What is the remaining global budget for carbon (or CO2 equivalent if we consider all greenhouse gases)?
2) *Apportionment* – What is a 'fair' apportionment of the budget across countries?
3) *Action plans* – What should each country be doing? Can targets be aspirational, or must they only be binding obligations?
4) *Support mechanisms* – Do some countries need support (technical, financial, etc.) to achieve their plans? Should the obligation to support be linked to historical over-emission or gross domestic product (GDP) measures? Can action plans be conditional on support?
5) *Implications/enforcement* – What happens if a country fails to meet its targets? What happens if a country's action plans don't align with apportionment? What happens if support doesn't materialize?

There are inevitable linkages across these factors. The first challenge is one of uncertainty, especially with regards to carbon space, often calculated as a carbon budget.[4]Significant attention is paid to carbon pricing (taxes or market mechanisms), border adjustment mechanisms, direct support or mandates (like renewable purchase obligations), etc., but many of these are in-country instruments. But the decisions around these spill over and impact the trajectories of other countries, some through macro trade and others through fossil-fuel and clean-tech related global markets.

The most pressing and contentious issue is figuring out emissions targets for all countries

The most pressing and contentious issue is figuring out emissions targets for all countries. Is the carbon budget meant to be cumulative including historical emissions or should it be calculated and apportioned only for prospective emissions? In this paper, we benchmark with a balanced apportionment, one that is beneficial to high emitters by ignoring the past, but also recognizes population differences for prospective budgets. Van den Berg *et al.* (2020) and Budolfson *et al.* (2021) examine alternative carbon budget apportionment models that include factors like

[3] The science tells us that total emissions should not exceed a threshold (by a particular time) for stabilization of temperature and prevention of irreversible damage to the ecosystem, within bounds of confidence. For a maximum rise of 1.5°C, the world should reach zero emissions by 2050, except in scenarios that rely on extensive removal of CO2 from the atmosphere afterwards.

[4] The concept of a carbon budget has inherent uncertainty and the budget listed for staying under a temperature rise of, say, 2°C is calculated with a qualifier, such as with 50 percent probability or confidence.

affordability, capabilities of reduction, and more. Appendix 1 goes into more detail on the impacts of apportionment mechanisms, but we purposely chose a balanced metric for this paper.

The Kyoto Protocol faced an impasse because developed and developing countries were treated differently. Compared to such historical attempts, the Paris Accord (COP21) was a break. It allowed each country to determine its contributions individually as Nationally Determined Contributions (NDCs). The Paris Accord embeds a consensus that all countries should improve emissions over time and ratchet up their ambitions. *However, a subtle but vital subtext of this framework is that historical emissions are excluded completely.* The rationale, ostensibly, was that we can't change the past, even though CO2 accumulates for centuries.

An important manifestation of this approach was that the NDCs were split – most developed regions pledged absolute reductions, but many developing countries pledged emissions *intensity* cuts, or relative cuts. Brazil was a notable exception.[5] The distinction between absolute and relative reductions is vital because developing countries need to still grow emissions to meet their human development imperatives. Few pathways for that don't raise their emissions.

While this accord was a step in the right direction, even if all countries meet their Paris commitments, we will, unfortunately, exceed an expected 2° Celsius rise in temperature. What makes this even worse is that most countries, especially developed ones, are not on track to meeting their Paris obligations (UNFCCC, 2021).

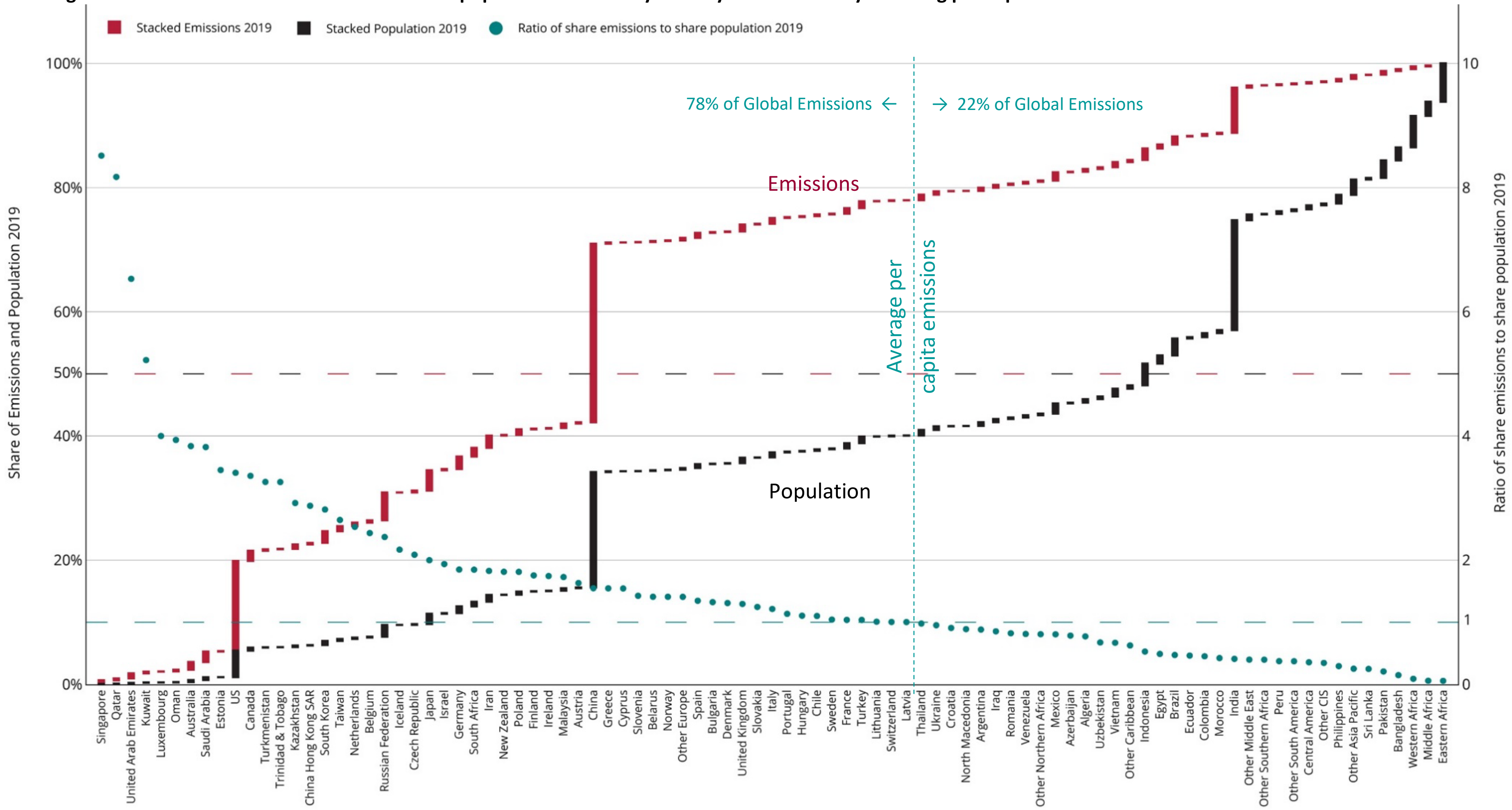
Above average per capita emission countries, who are a minority of the population, emitted 78% of global fossil CO2 in 2019

Figure 1 shows the skew in CO2 emissions across countries for 2019. It stacks emissions and population for the countries, ordering by per-capita emissions.[6] By the time we arrive at the point with the world average per capita emissions (vertical dotted line at Latvia), 'above average' emitters already account for 78 percent of 2019 global fossil CO2. If the world as a whole must reach zero by a particular date, say 2050, high emitters would need to reach zero sooner. Otherwise, the low emitters would also have to reach zero at the same time.

[5] A compilation of NDC pledges is available from Carbon Brief, at https://www.carbonbrief.org/paris-2015-tracking-country-climate-pledges.

[6] The BP Statistical Review of World Energy 2020dataset treats all fossil transacted within borders as attributed to the nation. This makes Singapore have the highest emissions due to extensive fueling of maritime vessels and its bustling port (and even airport). Almost all global accounting norms are based on production and not consumption and, thus, do not factor in exported embedded energy, which disproportionately impacts China. The BP (2020) data are only for fossil fuel use and exclude other industrial emissions from chemical processes and land-use/land-cover changes. These totaled over 34 gigatonnes (Gt) CO2 of global emissions in 2019, which is slightly different from National Emissions data. But the trends and apportionment across countries remain mostly consistent.

Figure 1: Global 2019 fossil CO2 emissions and population stacked by country and ordered by declining per capita emissions



Source: Fossil CO2 emissions calculated using BP data for emissions, and World Bank data for population.

Notes: The 50 percent horizontal line shows the median emissions country (China) and median Population (Indonesia). The world average per capita emissions are the lower dotted line with ratio 1, which crosses over between Latvia and Thailand. Countries with per capita emissions above the world average had 78% of CO2 emissions in 2019.

In this paper, we examine the fundamentals of emissions across countries and suggest a framework focused on the 'area under the curve' (total emissions) could be more equitable and also lead to lower emissions rather than a narrow lens of 'date of hitting zero'.

First, we examine the emissions from developing regions, showing how basic energy use doesn't account for large emissions. Next, we examine expected future emissions under compatible decline-to-zero trajectories and compare those for cumulative emissions. These are studied for a range of carbon budgets. We then show how the 'area under the curve' framework maps directly into planned carbon budgets, while net-zero pledges do not. We also consider the role of carbon removal and examine carbon pricing and its implications across countries.

Developing regions in context

Understanding developing countries is vital to future carbon scenarios. If we expect the world to move in a certain manner in aggregate, the trajectories of emissions will vary based on whether a country is a low or high emitter, which embeds issues like demographics and the economy. Developing countries overwhelmingly have low emissions (per capita) and a high growth ahead.

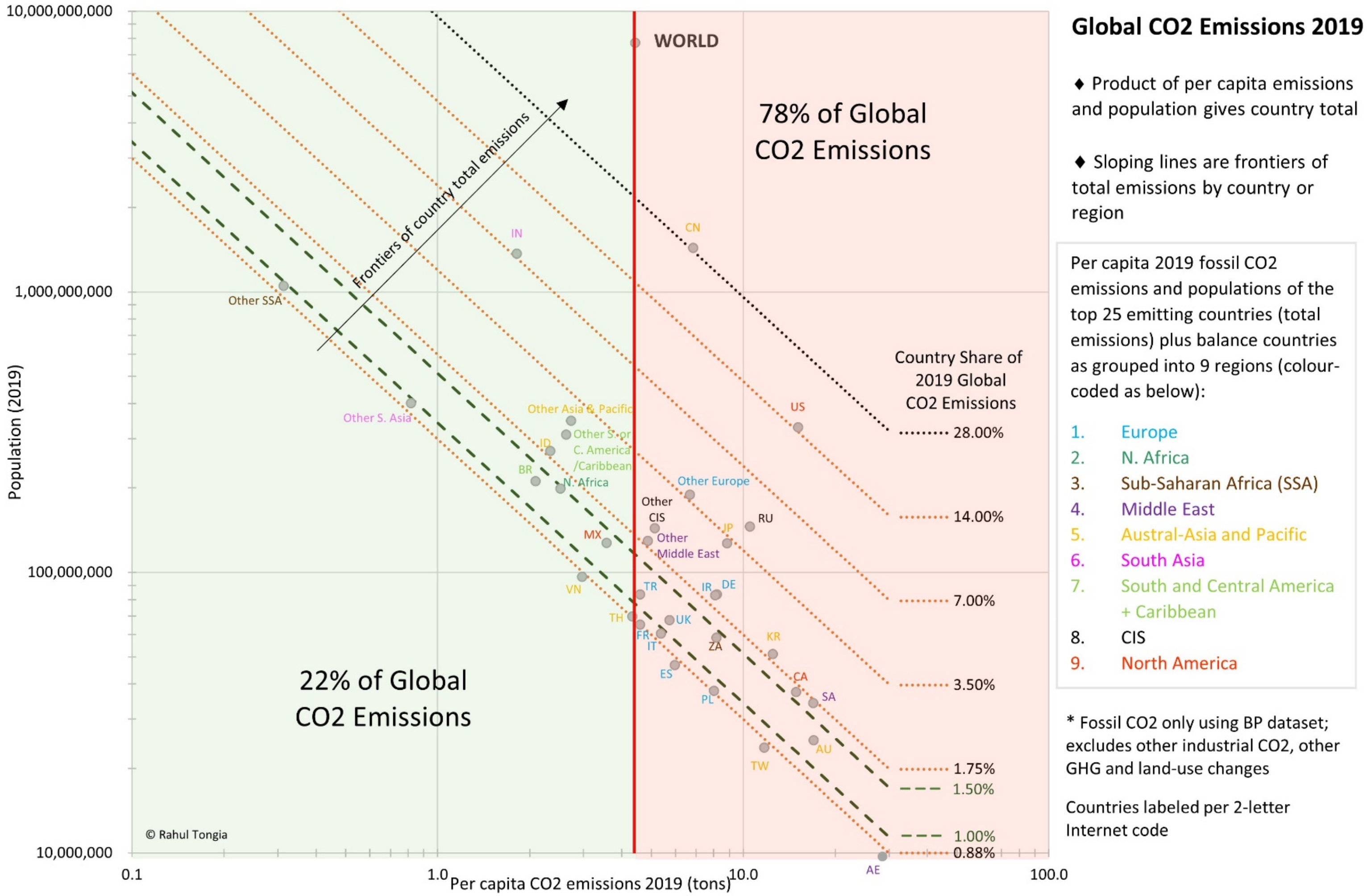
Low emitters are all from developing regions, but a few developing countries are high emitters, e.g., China. Its 2019 per capita CO2 emissions were about 50 percent higher than the world average, and it started its dramatic rise in emissions just after 2002.If we overlay its 2019 emissions with its roughly 1.5 billion population, China represents about 28 percent of fossil CO2 emissions globally, followed by the US at over 14 percent and India at over 7 percent.

These three nations are the most populous in the world and per capita emissions represent a better metric for their comparison to others. Figure 2 disaggregates the impact of per capita emissions versus population to explain total emissions by country or region. India's per capita emissions are far less than half the global average. Sub-Saharan African countries stand at an extreme. If we exclude South Africa, the remaining billion people of sub-Saharan Africa emit only a bit more than the under-10 million people in UAE do.

Given the extreme divergence in emissions, if the global target is zero by a particular time, it cannot translate to zero everywhere at the same time

Given the divergence in per capita emissions, the global target for zero cannot translate to zero emissions everywhere by the same deadline. Low emission developing countries need to raise emissions for some time. This will determine their likely trajectories for the coming years. However, by 2050 their emissions may not be much higher than they are today. In contrast, as we show subsequently, even if high emitters decline to zero emissions by 2050, almost all such countries would still emit more than most reasonable measures of 'fair share'.

Figure 2: Spread of countries total fossil CO2 emissions by population versus per capita emissions (2019)



Source: Fossil CO2 emissions calculated using BP data for emissions, and World Bank data for population.

Notes: The red vertical line splits the world into over-emitters and under-emitters, compared to the global average. The sloped lines represent frontiers of total emissions per country or region (identified using Internet 2-letter codes). Because this is a log-log graph, these appear as straight lines. China (CN) and South Africa (ZA) are developing countries, but high emitters. A billion people in Other Sub-Saharan Africa (excluding South Africa) emit only a little more than the UAE does, with under 10 million population.

Many developing countries are still grappling with the first rung of the so-termed energy ladder – basic access. They have large swathes, especially rural, where citizens still lack access to modern energy services, and rely on biomass for their energy needs. Sustainable Energy for All (SE4All), tracked by the World Bank (2018), found almost a sixth of the world's population, mostly in sub-Saharan Africa, lacked a connection to the electricity grid.

Electrification—with quality supply—is probably the most important consideration for most developing regions. It is especially important because many such countries, based on their geography, don't have space heating needs but require extensive cooling.

As electricity access grows, there is a clamour for these countries to avoid traditional development through the traditional grid, which may have relied on domestically available resources like coal. Experts hope, instead, they 'leapfrog' to renewable energy (RE)-based mini-grids. This is especially true for many post-COVID plans (e.g., articulated by SE4All (2020)). However, this ambition turns out expensive because quality RE supply needs extensive back-up. Also, given that new users consume less electricity, fixed costs, such as for last-mile wiring, dominate costs (Tongia, 2018). Sadly, such high costs hold true for the traditional grid as well, but such a grid design scales cost-effectively to meet rising demand.

Worries over the use of coal by the newly electrified are misguided…one billion new users supplied entirely with coal-power would add only 0.25 percent to global CO2 emissions

Carbon worries over use of coal by the newly electrified are misguided. If we supply a billion consumers (200 million homes) who lack electricity or quality supply connections through the traditional grid powered entirely by coal, and they use an above average first rung of electricity consumption (35 kWh/month, enough for a fan, TV, fridge, etc.), they would only add 0.25 percent to global CO2 emissions.[7] While decarbonization is important, ending energy poverty is more pressing. The actual impact of electrification would be even lower because few incremental supply solutions rely 100 percent on new coal – RE is the dominant growth for new electricity supply.

For developing regions, costs matter. This is a major reason they have relied disproportionately on locally available fuels, which can also provide jobs and energy security. This includes coal, even if it pollutes the air and soil. Appendix 2 has more details on coal versus other fossil fuels, and the differential impact of phasing out coal on some developing countries.

To help non-carbon energy displace fossil fuels, developed countries at Copenhagen COP15 in 2009 pledged to support developing countries with $100 billion annually by 2020. Monitoring how this has played out has been a vexing challenge. We need a much sharper definition of international *climate finance* flow. Much of the financing is for RE projects. However, that is business as usual (BAU) energy finance, focusing on RE that would be built anyway because it's now cheap. For such support to be meaningful, the principle of additionality should apply. Otherwise, this simply amounts to creative accounting. As Weikmans *et al.* (2020) point out, we currently treat a loan for a solar panel the same as a grant under climate accounting. The largest fraction of support under the Green

[7] Lifeline consumers (who get free power under the *Kutir Jyoti,* or *small-home light* program) served by BESCOM, the largest electricity distribution utility in Karnataka that encompasses Bangalore as well, only consume an average of about 12 kWh/month. This calculation is based on data from the FY2019 tariff order through the regulator. Most such users don't have a refrigerator, and many don't have a television. The emissions' calculations assume that coal power creates 950 gm-CO2 per delivered kWh, and global emissions are 37 Gt of CO2.

Climate Fund (2021) is simply debt-funding, and the share of debt is even higher if we consider mitigation projects.

Problems with net-zero pledges

Creative accounting is far worse in case of net-zero emission pledges than it is for climate finance. The word 'net' implies that the pledge is not necessarily for an absolute zero. Most countries and many companies rely on offsets, which raise multiple issues.

Carbon capture and sequestration (CCS), which is expensive, may already be included in future calculations of national emissions. Let's hope these aren't just kicking the can down the road. What do other offsets look like? If they are meant to be based on forestry and land-use changes, the time constants of carbon removal don't necessarily match those required (41 Scientists, 2020). Only actual capture and sequestration in the same year should count. Oxfam (2021) also points out the constraint of area – the land needed for plans announced so far would be the size of the Amazon, or one-third of the world's farmland.

The treatment of non-CO2 greenhouse gases is another unknown in the pledges of many countries (Rogelj *et al.*, 2021a). New satellite data suggest methane (natural gas), which has a much higher global warming potential (but a shorter atmospheric lifespan) than CO2, may suffer from much higher atmospheric release than previously estimated via inventory and economic activity-based accounting (Alvarez, 2018).

A global zero means that any inter-country credit or transfer offsets remain a zero-sum game. The premise of net-zero through adding offsets to compensate for adding new emissions is particularly bizarre. As Simon Lewis (2021) wrote:

A global zero means any inter-country offsets remain a zero-sum game…and some offsets are simply accounting tricks

> *'Mark Carney, the ex-governor of the Bank of England and climate adviser to Boris Johnson, recently described his $600bn Brookfield Asset Management portfolio as "carbon neutral", despite investing in fossil fuels. Carney said: "The reason we're net zero is that we have this enormous renewables business." He went on to claim that renewables avoid carbon emissions that would otherwise have happened, so they "offset" his investments in fossil fuel emissions. This is not net zero. It is an accounting trick.'*

Such offsets make avoided emissions equal to a negative emission while the original emission still occurs. This may reduce carbon growth but doesn't bring us down to zero.

Such offsets are even more problematic if developed countries take them from developing countries. McKinsey (2007)'s widely-discussed marginal abatement cost curves emphasize that the last fraction or tail of emissions is the hardest to decarbonize. Such an offset would mean that we are letting developed countries hold off their expensive terminal reductions in emissions by capturing carbon space from earlier-in-the-trajectory developing countries. What happens when developing countries also need to finally address their tail of emissions? There will be no cheaper offsets available for them. Their only saving grace is falling technology costs, but this is unlikely to be sufficient.

The biggest problem with net zero pledges is that they don't address the cumulative emissions of any country (area-under-the-curve)

The biggest problem with such net zero pledges is that they don't address cumulative emissions, i.e., the 'area-under-the-curve' of any country. Their only figure of merit is the years until zero.

There is significant heterogeneity in emissions across countries. For a number of high emission countries, even an immediate switch to a 30-year decline (zero by 2050) would result in their cumulative future emissions exceeding their *prospective-only* carbon budget.

Most stakeholders posit a quicker zero is difficult, both practically and politically. But if it's too difficult for developed regions to reduce so drastically, and some publications call this "inertia" (Rapauch *et al.*, 2014), it's also tough for developing regions to be constrained in their development ambitions and social imperatives. Appendix 1 has more information on carbon budgets and their apportionment.

Emissions growth in developing regions is likely to remain modest, often linked to GDP and development. Conversely, we don't want the unintended consequence of a net zero pledge to be a mad rush to emit upfront under the guise of rapid development. But that would be rational, just like diners may heap their plates when a buffet announces "last call".

Without additional metrics for staying within or improving on the carbon budget, the date of net-zero metric suffers from benchmarking future outcomes based on improvements to current behaviour, instead of cumulative emissions.

Net-zero date is attractive because it is simple, easy to compare, and visible – but it crowds out alternatives, and isn't sufficient to explain either what *should* be done or the cumulative emissions from a particular date

Unfortunately, we end up choosing such framings because they are simple, easy to compare, and visible. But they can crowd out alternatives. When the US announced 2006 tax credits for then fledgling hybrid electric vehicles, the credit was based on relative savings. This meant a huge SUV enjoyed the highest credit. This failed to recognize and incentivize the use of smaller non-hybrid vehicles, which would still use much less fuel than the hybrid SUV. Similarly, *we are applauding pledges of decades-later net zero from high emitters without rewarding those who have very low emissions, historically and in the present*.

The idea that 'earlier equals better' is misleading because it doesn't factor cumulative emissions. Like in the case of golf, we should have a handicap score to benchmark how 'good' a country's ambition is. This should be based on their carbon budget. The framework in this paper offers a metric for such a handicap by reconciling trajectories with their area under the curve (prospective cumulative emissions).

An alternative and richer emissions framework: Area-under-the-curve

Instead of choosing a fixed date, it would be better to work backwards, by first constraining emissions and then determining matching timeframes and trajectories. This lets us compare if, say, zero by 2050 is good enough for a country or not.

We can apportion the global CO2 budget across countries. There is some debate on the remaining carbon space we have globally.[8] This paper shows three different budget levels for comparison. These correspond to a maximum rise of 1.5°C (50 percent confidence), 2°C (66 percent confidence), and 2°C (50 percent confidence). More details on budgets are analysed by Rogelj (2021).[9] How to apportion the global budget is a more contentious issue. We use a balanced approach, one that actually benefits richer countries by ignoring affordability. Appendix 1 has more details on apportionment methods.

As remaining carbon budgets in this analysis are from the end of 2020, we use 2021 as the first year of prospective emissions. We assume that because of COVID-19 and subsequent economic recovery, the emissions per country in 2021 will be similar to those in 2019.

How much time we have left for a budget depends on the shape of the emissions trajectory. Many popular measures of 'remaining time', e.g., by the Mercator Institute (2021) or Zeke Hausfather (2018) under Carbon Brief, convert the budget based on *current* emissions levels. Based on 2019 emissions, simple arithmetic tells us that a 1.01 million tonne (Mt) or 1,010 Gt of *fossil* CO2 gives us under 30 years.

"Remaining time" should account for emissions trajectories, and current global emissions are still rising. Using historical data for moving averages for 3, 5, and 10 years, we find that the 3-year average may be most representative of expected trends in the near-term (ignoring any blip from COVID-19). While ten-year trends do smoothen out economic cycles, they are not appropriate due to the recent rise of RE as a viable option for electricity growth. On the bright side, it appears that emissions will come down, especially if a country pledged to start reducing them immediately and down to zero in (say) 30 years. If a country has sufficient budget remaining even after taking, say, 30 years to come down to zero, it could continue its present trend of emissions for some years.[10]

All countries would need time to come to zero; absent more specific pledges, the framework standardises on a linear decline to zero over 30 years, corresponding to a 3.33% annual decline

In this analysis, we apply the concept of a terminal decline over 30 years preceded by some years of emissions to match the leftover carbon budget, if any. For calculation's sake, the pre-30-year-decline period would continue with emissions "as-is" – with a trajectory of rise or fall based on a country's present (3-year moving average) emissions rate of change (Figure 3).

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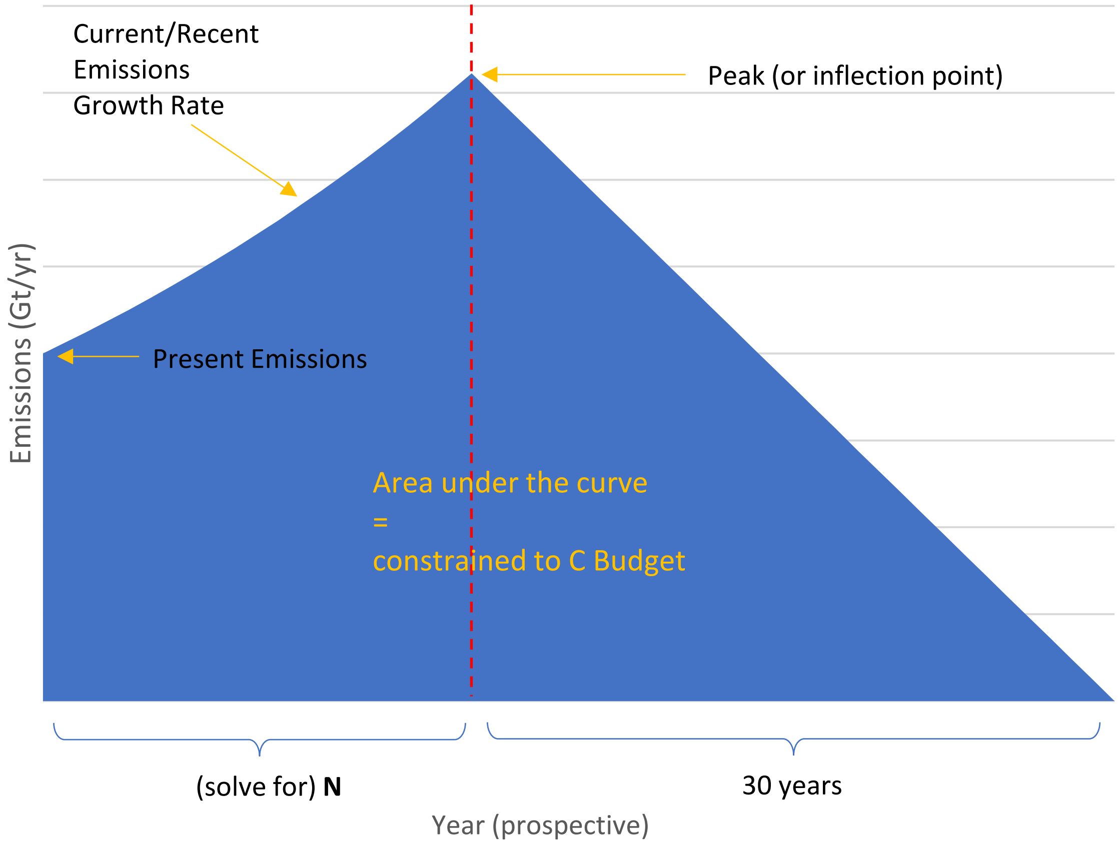
[8] Unlike changes in the mid-2010s, the recent IPCC (2021) AR VI Working Group 1 report didn't increase the uncertainty in the carbon budget for staying within a particular temperature bound, which will improve consensus around such numbers.

[9] Fossil-based CO2 emissions were just under 80 percent of total CO2 emissions, which add industrial processes (especially cement production) and land-use/land-cover (LULC) changes. The chosen fossil CO2 values in this analysis, 1,010 Gt, 750 Gt, and 280 Gt CO2, are the pro-rata fossil CO2 share out of total CO2 for limiting temperature rise to 2°C (50 percent confidence), 2°C (66 percent confidence) and 1.5°C (50 percent confidence), respectively. The global CO2 budgets are based on the summary by Joeri Rogelj for the UNFCCC (2021), which were 1,275 Gt, 945 Gt, and 355 Gt CO2 for the end of 2020, from which we adjust for fossil CO2 share to arrive at our numbers based on end of 2020. We assume that any anomalies due to COVID-19 and recovery smoothen out.

[10] A right triangle shape declining to zero has half the area of a rectangle of the same dimensions, which is what calculations for "years remaining" use based on *current* emissions.

Figure 3: Area-under-the-curve framework - allocating carbon while enabling graceful declines to zero



Why are we using a 30-year linear decline across countries? For this framework, the exact number of years is secondary as long as it is consistent for all countries. The year 2050, the target pledged by some countries,[11] corresponds to a 30-year decline when 2021 is counted as the first year. This timeframe also corresponds to a 3.33 percent annual decline, if achieved equally (linearly). This could be manageable with improvements in energy efficiency or productivity combined with a graceful end-of-life for infrastructure. But that holds true only if energy services are universal and infrastructure is saturated. This is not yet the case in developing countries, which makes their delay in starting such a decline inevitable.

There are hopes that early decline in emissions can be rapid, based on low-hanging fruit such as solar and wind power. On the flip side, there it is difficult to remove the tail-end of emissions, especially in industry and extensive infrastructure build-outs. If we consider a sideways S-curve shape—rapid decline, then a mid-plateau, followed by a sharper terminal decline near the end of 30 years—the cumulative emissions are the same as with they would be with linear decline, as long as that shape is symmetric.[12]

Until a more credible emissions curve is available, for the sake of comparison we assume such a triangle-shaped trajectory for a linear decline declining to zero over 30 years. The remaining budget before the peak or inflection point can be set up to solve for "N" number of years, during which

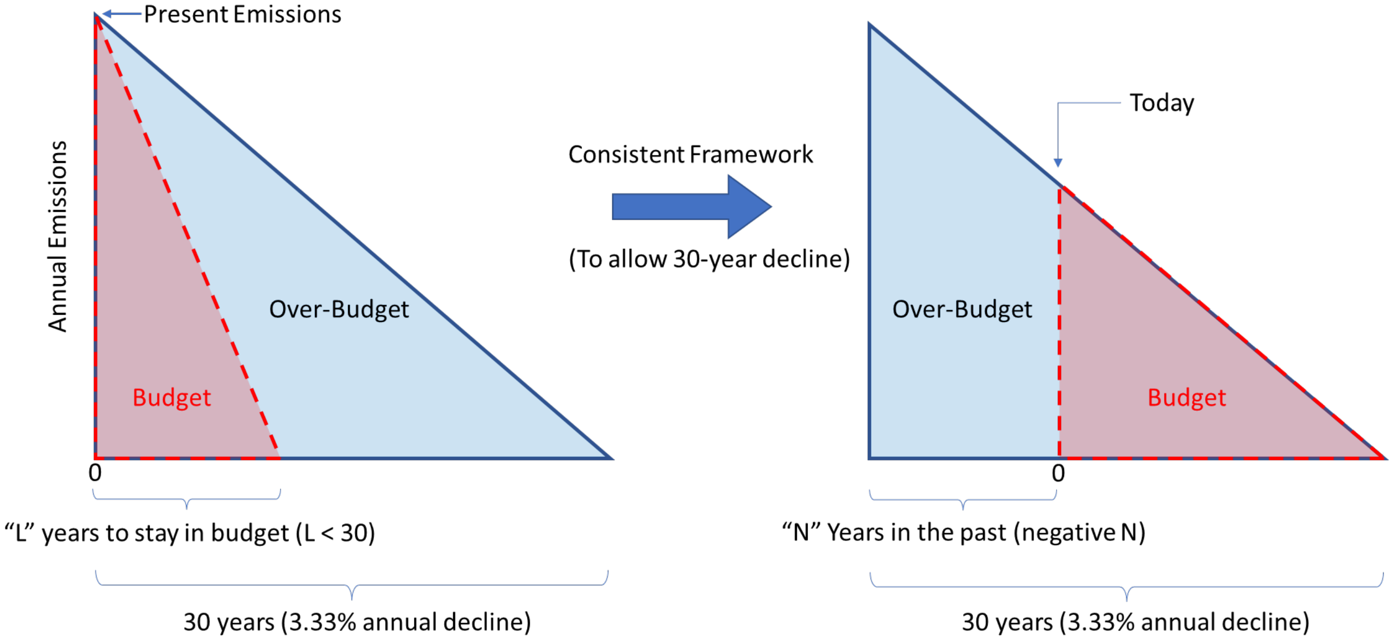
[11] A handful of countries have pledged more aggressive zero-dates, but they are outliers.

[12] A 3.33% *absolute* annual decline is harder than it appears because over time the base on which it applies is shrinking. Halfway through, it would translate to a 6.66% relative decline. An exponential (CAGR) type decline requires an even greater initial decline. Just to reduce emissions in 30 years to 5% of present emissions would require an annual (CAGR) reduction of -9.5 percent.

current emissions growth can continue (calculated here using the 3-year average rate through 2019, "r") while keeping the total area under the curve within the country's respective budget.

High-emitters may not have 30 years left for a linear (triangle-shaped) decline to stay in budget (Figure 4). If "L" is the number of years they have to arrive at zero emissions to stay in budget, and L<30, they need an annual decline much steeper than 3.33 percent.

Figure 4: High emitters would break their budget if they take 30 years to decline



Notes: A negative "N" indicates that the country should have started its decline to zero emissions in the past to allow for itself 30 years of decline. Due to non-linearity, 'Y' ≠"N". For example, if "Y" (years for linear decline) were 15 years (half-way), the budget and over-budget would be equal, but if "N" were -15 years (halfway), the over-budget would be three times the budget.

To allow a consistent comparison across all countries that have 30 years to linearly reach zero, for high emitters the mathematical solution to staying in budget is a negative value for "N". This means they should have begun their 3.33% annual decline in the past. While this is a hypothetical thought exercise, even the high rate of annual decline, depicted on the left side of Figure 4, is also a hypothetical. Very few countries have beaten the 3.33 percent annual emissions decline threshold (the lower portion of Figure 5, which shows the current rate of emissions change "r" based on the 3-year moving average through 2019).

How does the global average distribute across countries?

Table 1 shows the global solution for "N" for different carbon budgets.

Table 1: Global time remaining ("N" years 'as-is') to stay in budget

	Global Budget 280 Gt fossil CO2 (1.5°C max rise with 50% confidence)	**Global Budget 750 Gt fossil CO2 (2°C max rise with 66% confidence)**	**Global Budget 1,010 Gt fossil CO2 (2°C max rise with 50% confidence)**
"N" years globally	-7.8	5.6	11.4

Notes: These are based on end of 2020 as the reference year. After this period N, there remains the consistent 30 years of decline to zero. For the stringent carbon budget, we don't have 30 years remaining. For the other *two cases, emissions continue their trajectory with a growth of "r" = 1.2 percent, based on the 3-year average through 2019. Different countries would, naturally, have different values for "r".*

The bad news is that if we aim for a limit of 1.5°C rise (that too with 50 percent confidence), we don't have 30 years for a linear (triangle-shaped) decline (as generalised in Figure 4). Globally, we should have started 7.8 years before 2021. If we want a carbon budget commensurate with a 66 percent confidence of staying within 2°C, we have only about 5.6 years left (from the end of 2020). For the most generous budget, corresponding to 2°C rise with 50 percent confidence, we have 11.4 years. This is the global figure – different countries would have their own respective values.

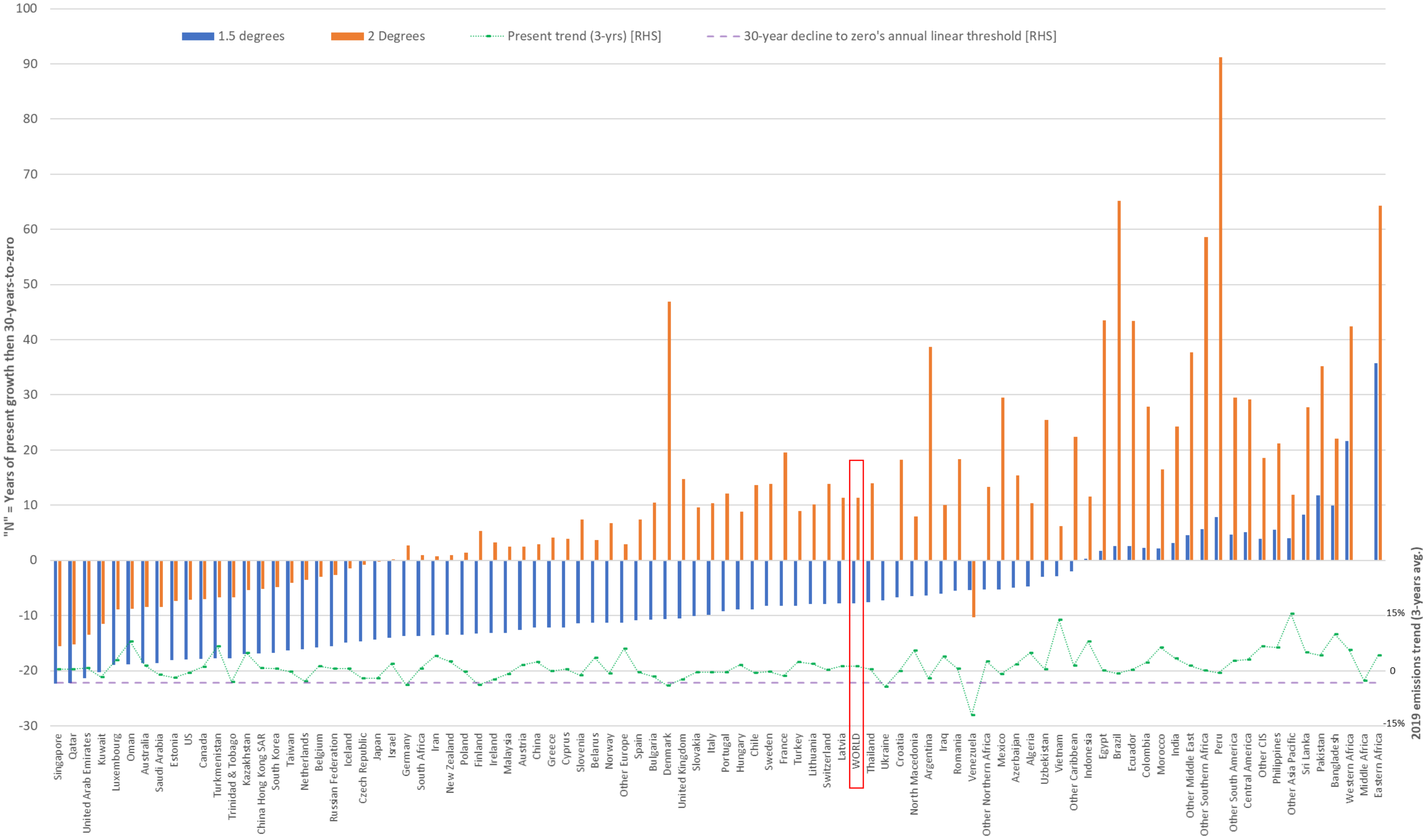
This framework does not solve for the exact zero-date of 2050 as per IPCC. The difference depends on the budget assumed, but more on non-fossil CO2, other greenhouse gas, and land use/land cover changes. The difference is also, in part, due to the intricacies of sequencing reductions and trajectories. Without considering climatological cycles, this framework simply spreads out budgeted emissions under varying trajectories. However, the trends and inter-country differences in this framework are relevant, and robust.

Low emission countries could emit more for "N" more years before peaking, but high emission countries have less than 30 years to decline to zero and still stay in budget (solving as negative "N")

These global averages mask substantial heterogeneity across countries. The differences are based not just on 2019 baseline emissions or respective carbon budgets, but also on how they perform in the years ahead.

Figure 5 shows the country-wise number of years "N" for which a country can continue as-is until it begins its terminal decline to zero, ordered by decreasing per capita emissions today. By comparing the trends for 2°C (orange) versus 1.5°C (blue), both with 50 percent confidence of staying within the temperature rise, we see many non-linearities. While this may appear complex, it reflects the reality of current emissions, trends, and budgets, in a way that a simple 'year of zero' cannot.

Figure 5: Area under the curve calculations - solving for “N” years of ‘as-is’ annual change before a 30-year decline to zero to stay within CO2 budget



Notes: This graph shows the number of years ("N") before a country must begin a 30-year decline to zero and still stay within its carbon budget for 1.5°C or 2°C rise (50 percent confidence) based on the area-under-the-curve framework. The lower portion shows the current (3-year average) annual rate that continues for "N" years, along with a threshold for 30-years to come to zero linearly. Some countries have negative "N", meaning they would over-emit, even if they immediately began a linear decline to zero in 30 years (achieved 3.33 percent absolute reduction from now annually). A few countries don't converge to a solution due to their negative trends overlaid with their present emissions, e.g., Venezuela for high budgets or Middle Africa (all budgets).

If we are targeting a 1.5°C rise (blue bars), only a few countries or groups have any time left for continuing current growth.

Even with the generous budget corresponding to a 2°C rise—the orange bars in Figure 5—many countries (crossing over between Japan and Israel on the graph) break their budget for a rise of 2°C. They solve for negative values of "N". If we want a 1.5°C rise cap, the 30 years of decline to zero emissions should have started in the past for countries all the way up to Indonesia on the graph. While not shown here, the calculation for a rise of 2°C (66% confidence) is in-between, with a cross-over by Slovenia.

The growth rate in the near-term (before peaking or inflection) matters enormously when calculating the total emissions and time we have to stay within budget. A low or even negative growth rate ("r") adds years of allowed emissions while keeping countries within the budget.[13] We also note there is no strong trend-line between per capita emissions and present growth rates (three-year averages to 2019) (shown as the lower green markers). There is a small negative correlation, -0.17, between the average unweighted growth rate and per capita emissions (i.e., not adjusting for size of country). But there are many countries with high emissions per capita but still a high positive growth rate of emissions. Almost no country is below 3.33 percent annual decline threshold that translates to a 30-year decline (shown as the purple horizontal dashed line).

If we examine key countries, their announced net-zero dates appear weak – they would over-emit

If we examine key countries, their announced net-zero dates appear weak. High emitters bust their generous budget even if they start their decline immediately. For China, we have a second issue. We don't know their emissions trend until peaking. Even with the most generous budget (2°C with 50 percent confidence), they should reach zero emissions in 33 years ("N" = 3.2 from the base year, which is the end of 2020). India, which has very low emissions, could continue growing at 3.43 percent for 24.3 years from the start of 2021 before starting its 30-year decline to zero. In fact, it would peak 8 percent lower than the global average per capita emissions of 2019, even after ignoring population growth, with peak per capita emissions 41 percent lower than China's 2019 emissions.

If we compare "N", the remaining time select countries have of 'as-is' emissions before the terminal decline (Table 2), very few have remaining time before they have to peak emissions. If our objective is a maximum rise of 1.5°C (that too with just 50 percent, not 66 percent, confidence) they many of these countries should already have started reducing emissions by 3.33 percent annually, that too in absolute terms from the peak.

[13] A handful of countries have sharply negative 3-year trends, and their cumulative emissions do not converge to equal their budget, e.g., Middle Africa, or Venezuela for its 2°C calculation. It is unlikely they can (or even should) continue such a negative emissions growth rate given their low emissions and low human development indicators.

Table 2: Time "N" remaining for selected countries to stay within their carbon budget as per the framework

	Per capita fossil CO2 emissions 2019 [tons]	2019 3-year average YoY emissions trend (as extrapolated) = "r"	"N" = Years 'as-is' rise/fall to stay within 1.5°C rise carbon budget followed by a 30-year decline	"N" = Years 'as-is' rise/fall to stay within 2°C rise carbon budget followed by a 30-year decline	Pledged date of 'net-zero' or carbon/climate neutrality	Pledge Sufficient to match "N" for 1.5°C rise?
UAE	28.92	0.69%	-21.3	-13.5	*no pledge*	n.a.
USA	15.09	-0.49%	-18.0	-7.2	2050 (statement of intent)	*NO (No change)*
Canada	14.87	1.15%	-17.9	-7.0	2050	*NO (No change)*
Russia	10.51	0.64%	-15.6	-2.7	*no pledge*	n.a.
Japan	8.85	-1.99%	-14.3	-0.2	2050	*NO (No change)*
S. Africa	8.18	0.59%	-13.7	0.9	2050 (policy position)	*NO (No change)*
Germany	8.19	-3.88%	-13.7	2.7	2045	Insufficient
China	6.85	2.45%	-12.2	2.9	2060	Worse than 30 years
WORLD	4.43	1.24%	-7.8	11.4		
UK	5.73	-2.35%	-10.5	14.7	2050	*NO (No change)*
France	4.59	-1.37%	-8.2	19.6	2050	*NO (No change)*
Bangladesh	0.65	9.96%	9.9	22.1	*no pledge*	n.a.
India	1.82	3.43%	3.1	24.3	*no pledge*	n.a.
Brazil	2.09	-0.66%	2.6	65.2	2050	*No change*

Source: Net-zero pledge dates are as per Climate Change News (2021) compilations, except for Brazil's updated date as per news reports.

Notes: "N" is the time before the common 30 years-to-zero decline. A negative number indicates there is insufficient time to allow the subsequent 30 years decline to zero – the linear decline should have started this many years in the past. For these countries a 2050 net-zero pledge would be considered weak, even after assuming they reach zero linearly with a 3.33 percent annual decline from the peak, which is the starting point for the 30-years' decline. 'As-is' means continuing the emissions trend as of 2019 (3-year moving average).

The countries are ordered based on their remaining time to stay within the 2°C budget (50 percent confidence). The variation in current trends explains why the current emissions don't directly indicate years left, and why the order of countries shifts between 1.5°C versus 2°C rise. While the US and Canada have similar current emissions, the negative trend of the US becomes moot since both countries have zero years of remaining growth 'as is'.

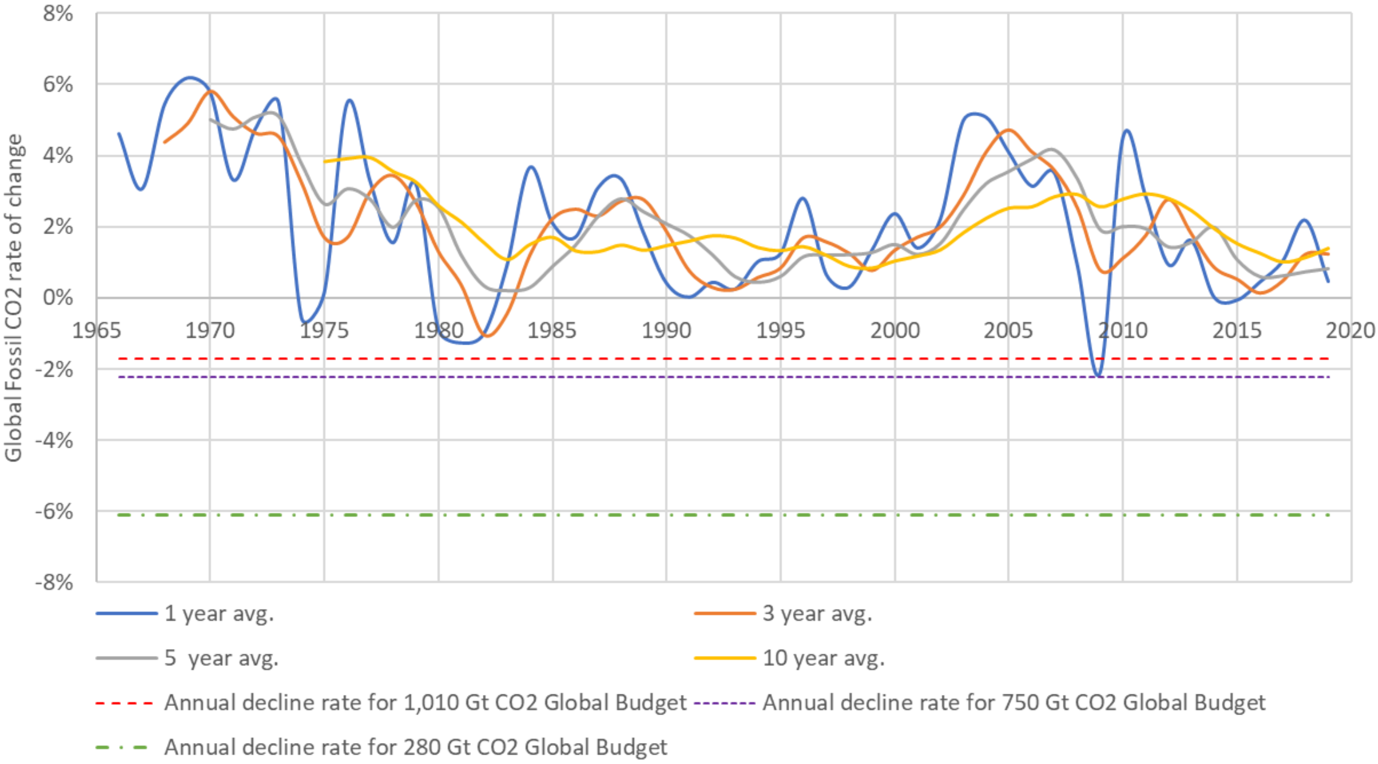
In no case does a zero date before 2050 overcome the over-emissions to stay within a 1.5°C rise budget.

What do negative numbers mean, considering one cannot go back in time? As shown before, in this case they imply that an even more challenging rate of annual decline is required for a country to stay in budget (left side of Figure 4). For a 1.5°C rise, N = -7.8 years globally. If the world started 7.8 years ago, it could have had 30 years of 'gradual' decline (3.3 percent annually, which is unprecedented). In prospective terms, to stay within this aggressive budget, the world needs to zero out in a mere 16.4 years, along a linear decline ("L" years in Figure 4), which amounts to 6.1 percent decline annually!

While a few countries have announced more aggressive net-zero dates than 2050, these aren't sufficient to overcome the reductions necessary for them to stay within budget. Due to non-linearities, one year of negative "N' amounts to more emissions to overcome than one year of faster linear reduction to zero ("L").

It's important to recognise that we don't know the prospective shapes of emission trajectories. Globally, as with each country, we have many year-on-year variations. Unfortunately, since 1965, we have never had a long-term or even a medium-term decline in the average annual global CO2 that is close to 2 percent. This has not happened even during recessions. All three-year averages have been positive, except during early 1980s (Figure 6). 5-year and 10-year moving averages have also all been positive. Even the unusual blip caused by COVID-19 is unlikely to lead to sustained declines when we apply a moving average.

Figure 6: Global Y-o-Y CO2 changes in fossil CO2 emissions



Source: Calculated from BP Statistical Abstract of Energy 2020 data. Fossil CO2 data exclude other industrial emissions, other greenhouse gases, or land-use/land-cover changes.

Notes: The 1 year moving average means no averaging. Multi-year averages smooth out economic and other cycles.

The horizontal dashed lines are the required linear annual declines to meet 1.5°C (50% confidence), 2°C (66% confidence), and 2°C maximum rise (50% confidence), corresponding to 280 Gt, 750 Gt, and 1,010 Gt CO2, respectively.

Using the 30-years decline benchmark, translating to a linear decline of 3.3 percent annually in absolute terms, only five countries or blocs have had a 3-year decline better than this threshold.[14] Some of these may have been blips or economic downturns, e.g., Venezuela (lower green lines in Figure 5).

While the future should show improvements over past rates of emissions change, we've never come even close to necessary sustained rates of emission reduction

It is true that there is now pressure to decline emissions rapidly and technologies to this end are improving as well. However, even if many countries are able to achieve high rates of reduction in emissions for extended periods, it is unlikely that this will be achieved across countries for 30 years. The decline trend line even for high emitters, shown in Figure 16 in Appendix 3, is not much lower than the global average.

A country's solution to "N" depends on how much their apportioned carbon budget is. Appendix 4 shows results with different techniques for allocating the global budget. Some are explicitly unfair to low emitters (e.g., continuing current emissions for apportionment needs, and calling it inertia). It turns out that apportionment alone doesn't tell the story. The global budget selected is also a non-linear factor for comparing how much time countries have before they need to begin their decline. For high emitters, if we target a stringent global budget for 1.5°C rise, even a generous allocation doesn't help them much when measured by the total years until they should reach zero (Table 9 in Appendix 4). The real need is to focus on a tight budget, ideally commensurate with 1.5°C temperature rise as the limit. However, this shouldn't become an excuse to become generous to high emitters with weightage for inertia.

Flattening the curve – lowering the emissions trajectory

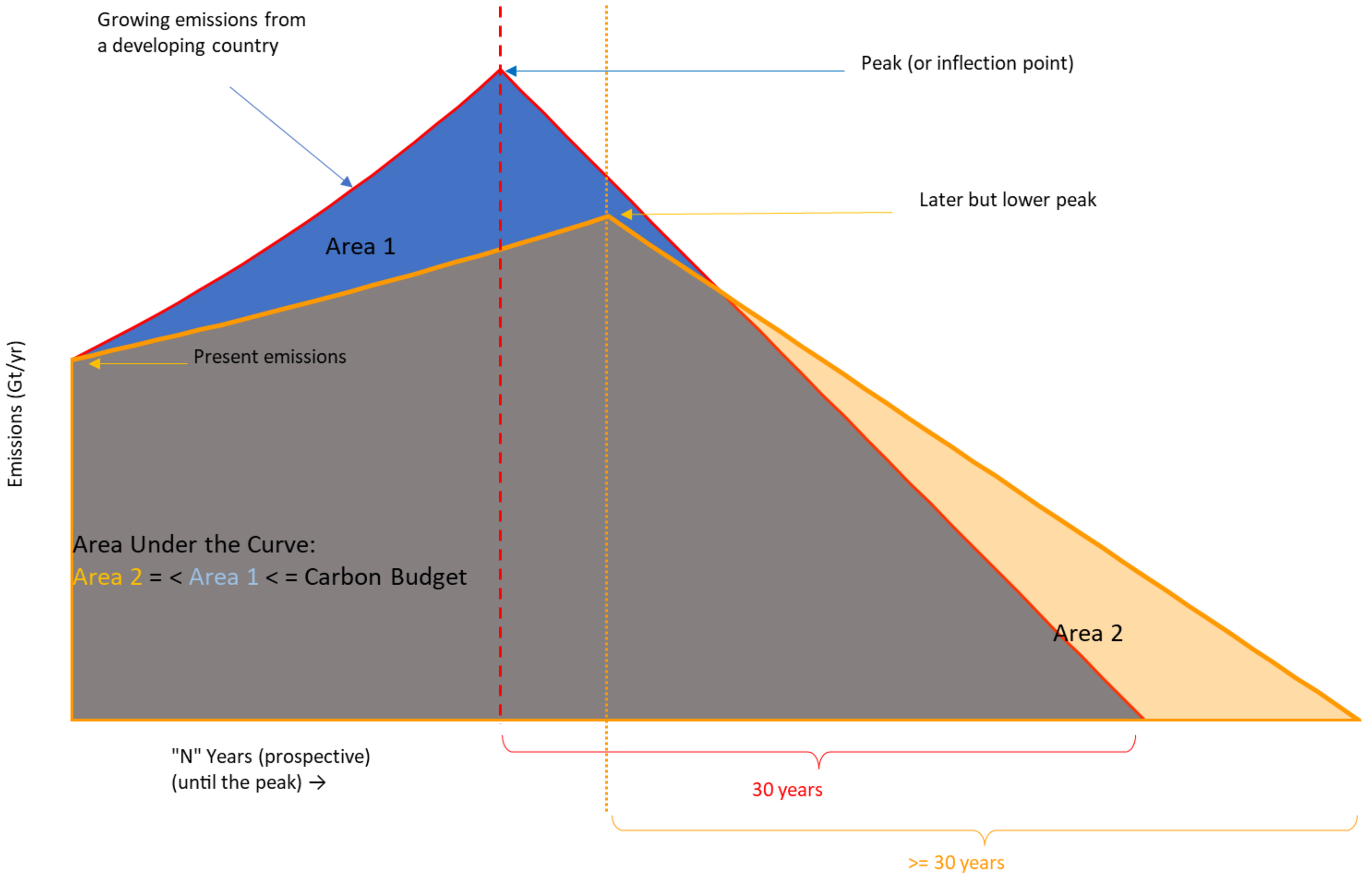
An area-under-the-curve framework can compare countries equitably, based on how long it they can take to come to zero emissions, while also adding a layer to acknowledge that the short-term emissions trajectory will be distinct from the terminal decline to zero (over 30 years). Cumulative emissions are based on a combination of current emissions and expected near-term trajectories, constraining their respective areas under the curve.

This framework also enables a focus on improving trajectories, which can vary. All countries have the opportunity to accelerate reductions during their terminal decline by taking less than 30 years so that cumulative emissions are lower for their triangle (declining) phase. Such action can reduce temperature rises.

For developing regions (low emitters), the additional possibility is to lower their growth rate of emissions in the earlier part of their emissions trajectory. If nothing else changes, such as taking "N" years to peak, this would lower their emissions. Alternatively, another implication of a lower growth rate is to spread out emissions over a longer time frame, i.e., to flatten-the-curve.

[14] Countries with a three-year average year-on-year fossil CO2 decline greater than 3.33 percent through 2019 were Venezuela, Ukraine, Denmark, Finland, and Germany.

Figure 7: Flattening the curve: Cheaper and potentially lower total emissions



Notes: This framework allows changing the years "N" until the inflection point by following a different growth rate "r" from the present (2019) until the inflection point (peak). This changes the year of zero emissions, but it can also lower the cumulative emissions.

COVID-19 taught us flattening the curve to avoid exhaustion of medical capacity even if the infections remain the same. Here, a pure flattening of the curve would similarly not change total cumulative emissions, but thanks to falling costs over time, *a later but proportionally lower peak would mean measurable cost savings.*

"Flattening the curve" would lead to a combination of lower total emissions and/or lower costs – some countries should aim for a *later* but *lower* peak

In addition to keeping total emissions constant, there is a high chance we can lower the total emissions because of improving technologies and greater decoupling of GDP (development) from emissions over time. There is no reason India should emulate China in terms of rapidly growing emissions like China did almost 2 decades back. Nonetheless, it is illuminating to examine how many years behind China India is in terms of per capita emissions; India is less than half the world average today. In 1990, China's emissions were 20 years ahead of India (it emitted the same back in 1970) but by 2019, China was over 27 years ahead. In fact, China accelerated its emissions early to mid-2000s, and at current trends, India is many decades behind China. Adjusting for population (per capita emission *trends*), the gap gets even higher.[15]

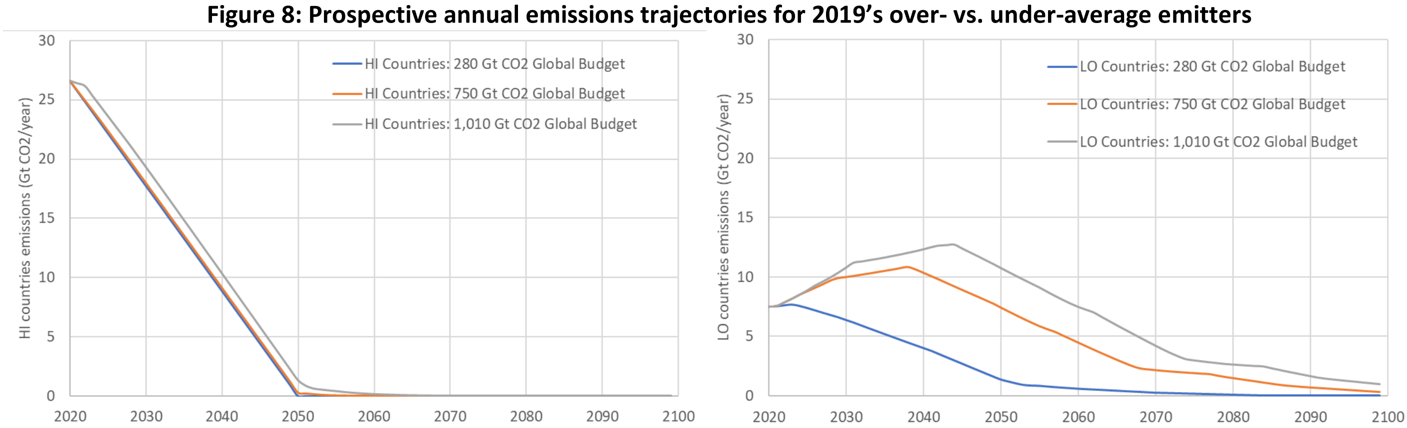
Why is comparing "N" years better than simply comparing date of zero? After all, we can add thirty years (the chosen linear decline years) to "N" to calculate the year of zero with this framework. It is better because it focuses on how long you can continue "as-is", which starkly distinguishes between countries that should have already begun their decline and those who have a little time – *and more time if they are able to flatten the curve*. A negative number also directly tells us that a 30-year decline to zero is still over-emission based on the chosen budget and apportionment.

Implications of the trajectories – We're headed for bust

This framework brings to the fore issues of "over" and "under" emissions. Grouping countries as HI and LO emitters based on being above or below the average per capita emissions in 2019, we find vastly different trajectories for these two groups across various global budgets (Figure 8). These trajectories assume countries with a negative "N" can't further accelerate reductions to stay in budget beyond a 3.33 percent annual decline, and over-emitters still take 30 years to zero. As we've shown in Table 2, even a few years faster decline to zero isn't sufficient for many high emitters, and even if some countries beat the trajectories assumed here, the total savings from this handful of countries are drowned out by the shortfalls from other countries.

On the flip side, it also isn't necessary that LO emitters should take so long to reach zero, and with support they should be able to do better. This is despite the area-under-the-curve framework enabling them to zero later and still stay in budget.

Figure 8: Prospective annual emissions trajectories for 2019's over- vs. under-average emitters



Notes: This splits countries into HI and LO groups based on per capita emissions being above vs. below the 2019 global mean. It then applies an area-under-the-curve framework per country (solving for "N" years of possible rise, followed by a 30-year decline to zero) to aggregate countries into the above graph. Importantly, for countries with negative "N", for comparison's sake, we assume they still take 30 years to reach zero. Hence, such countries bust their budget.

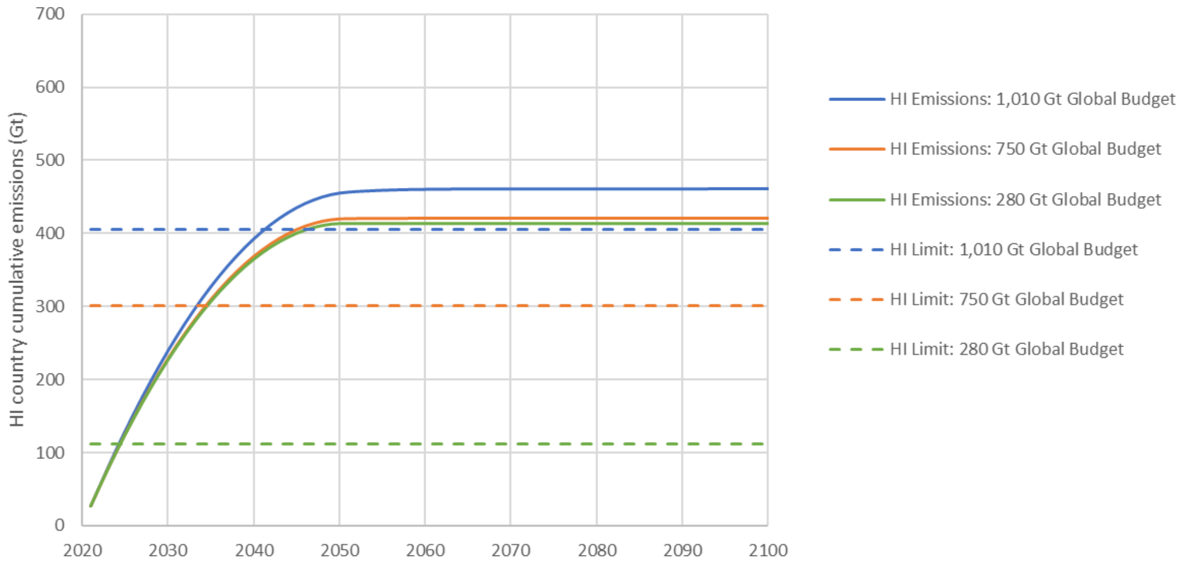
[15] Rising populations shouldn't offer an open-ended rise in emissions. Any carbon budgeting should pick an anchor year for populations if population-adjusted (per capita) figures are used, whether it's 1990, 2000, or even 2020.If we're apportioning global carbon budgets only on a prospective basis, then 2020 populations would be appropriate.

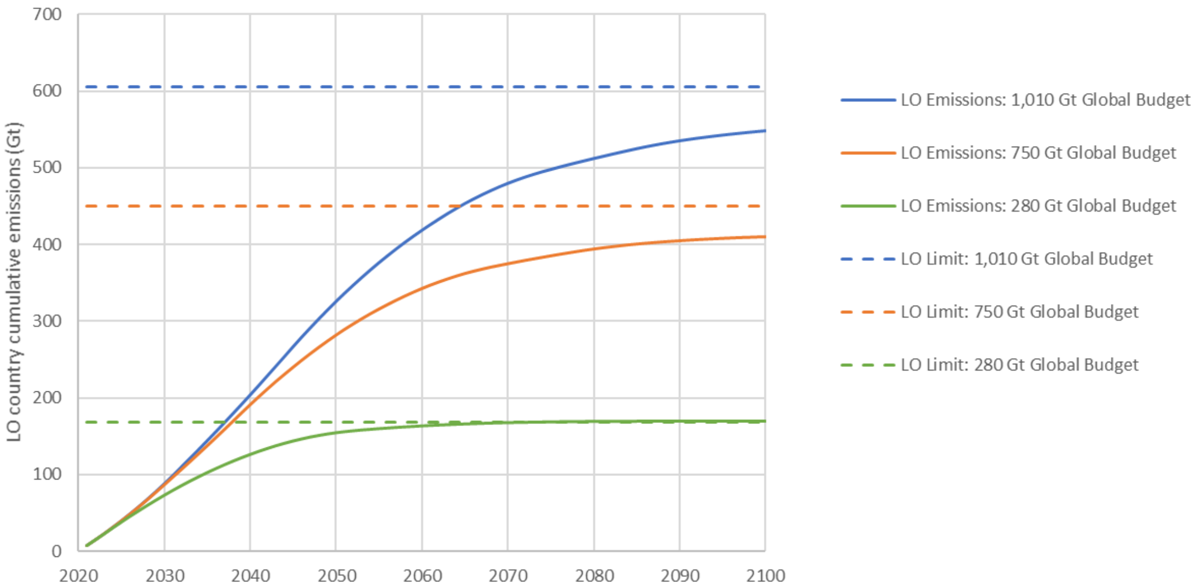
For LO countries, this framework allows for a longer tail of emissions but with a much lower peak. This example applies 3-year averages through 2019 for YoY growth per country. The remaining three global carbon budgets correspond to 1.5°C (50% confidence), 2°C (66% confidence) and 2°C (50% confidence) rise.

High-emission countries (with per capita emissions over the world average) are projected to be unable to decline to zero fast enough, and are likely to emit more than their budget allows

Given the negative "N" for HI emitters is unlikely to be overcome through sufficiently aggressive declines to zero (faster than 30 years), this leads them to over-emit in aggregate compared to their budget (Figure 9). In contrast, LO emitters, in aggregate, stay under budget through 2100.

Figure 9: Cumulative fossil CO2 emissions versus respective budgets for HI and LO emissions countries





Notes: This figure shows cumulative emissions of fossil CO2 for HI and LO countries grouped as those with above and below average per capita emissions in 2019. For all three scenarios of global carbon budgets, HI emitters over-emit, mainly because a 30-year decline to zero is too slow for them to stay within budget. For the LO emitters, they stay within budget except for a trivial overshoot under the scenario of 1.5°C (with 280 Gt Global CO2). In many carbon budget scenarios, the LO countries don't entirely use up their budget even by 2100. This suggests those countries can increase their growth "r" compared to the past and still stay in budget.

The three remaining global carbon budgets (Mt) correspond to 1.5°C (50 percent confidence), 2°C (66 percent confidence) and 2°C (50 percent confidence).

Global action plans

High emitters need to reduce their emissions immediately and dramatically and also move to true zero; developing countries need to peak as low as possible and avoid locked-in pathways

If the old system was meant to be designed around "common but differentiated responsibilities", an 'area under the curve' framework allows us to focus on *universal but differentiated actions*. Developed countries (rather, high-emitters) need to reduce their emissions immediately and dramatically, and move to true zero. Developing countries need to peak at as low a level as possible and avoid locked-in pathways, corresponding to lower growth rates of emissions until they peak.

HI and LO groupings were earlier made at a country level. We can also aggregate these countries into various groups to help us understand geographies of relevance. Table 3 shows such groupings. Here, the US, China, EU-27, Other Europe, Russia, Japan, Other OECD, and Middle East are above average. These eight countries or blocs are also responsible for just under 78 percent of global emissions, similar to the share for HI emitters aggregated at country level. Focused action by these groups would be vital for not just lowering their emissions but also paying down learning-curve costs for technology, which can also be used subsequently by low-emitters.

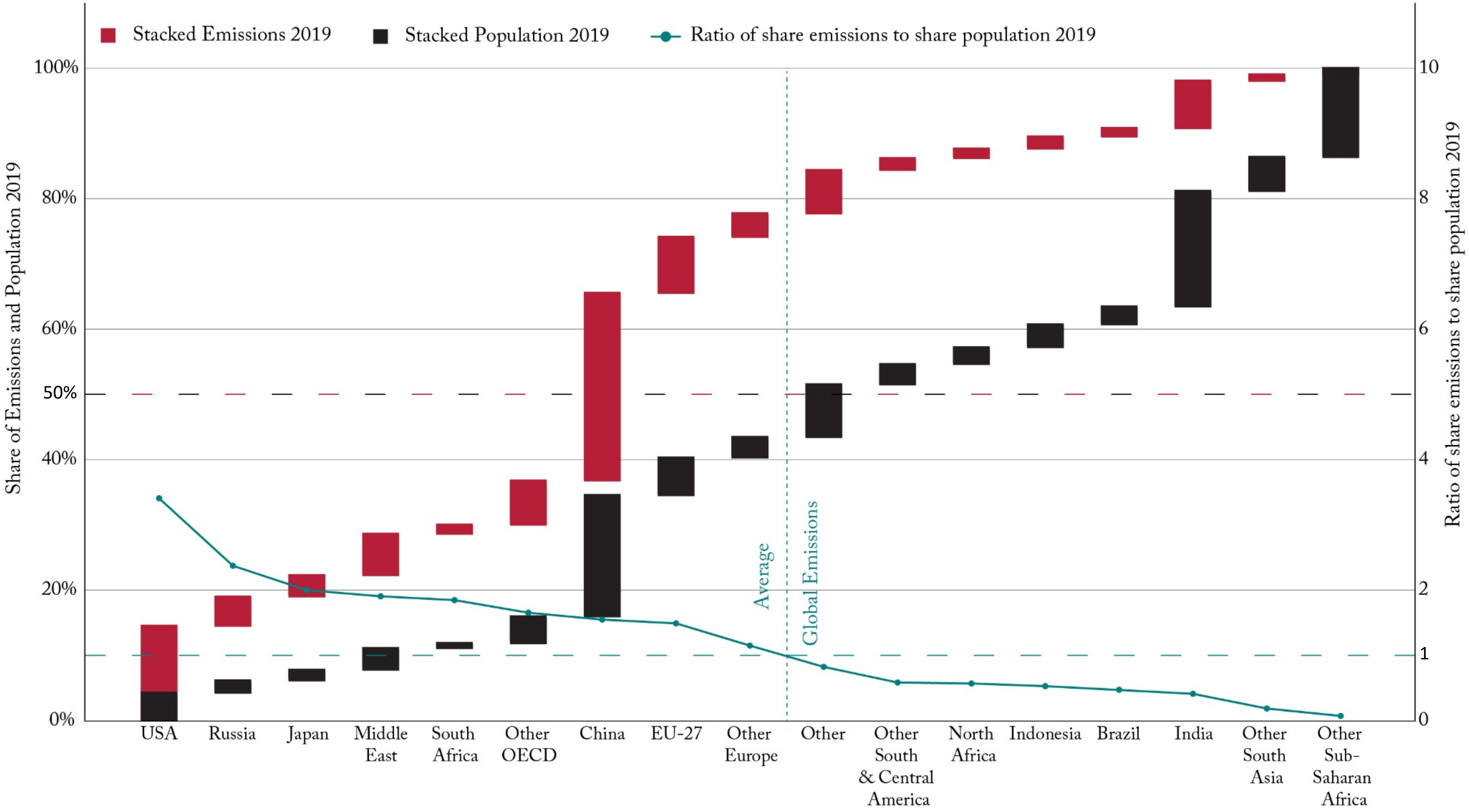
Table 3: Emissions (2019) of major countries or groups, separated as above and below average emissions

	2019 Fossil CO2 (Mt)	Population 2019	2019 Emissions per capita (t CO2)	Share Emissions 2019	Share Population 2019
China	9,826	1,433,783,692	6.85	28.8%	18.6%
USA	4,965	329,064,917	15.09	14.5%	4.3%
EU-27	2,933	444,546,391	6.60	8.6%	5.8%
India	2,480	1,366,417,756	1.82	7.3%	17.7%
Other OECD	2,309	315,489,628	7.32	6.8%	4.1%
Other	2,268	622,462,446	3.64	6.6%	8.1%
Middle East	2,164	256,608,296	8.43	6.3%	3.3%
Russia	1,533	145,872,260	10.51	4.5%	1.9%
Other Europe	1,237	243,019,795	5.09	3.6%	3.1%
Japan	1,123	126,860,299	8.85	3.3%	1.6%
Indonesia	632	270,625,567	2.34	1.8%	3.5%
Other South and Central America	621	240,225,107	2.58	1.8%	3.1%
North Africa	501	198,967,528	2.52	1.5%	2.6%
South Africa	479	58,558,267	8.18	1.4%	0.8%
Brazil	441	211,049,519	2.09	1.3%	2.7%
Other Sub-Saharan Africa	329	1,050,538,365	0.31	1.0%	13.6%
Other South Asia	328	400,935,224	0.82	1.0%	5.2%
WORLD	34,169	7,715,025,057	4.43	100.0%	100.0%
Above Average	26,568	3,353,803,545	7.92	77.8%	43.5%
Below Average	7,601	4,361,221,512	1.74	22.2%	56.5%

Notes: The groups with 'other' exclude those countries captured elsewhere, e.g., Germany is OECD but captured in EU-27 (and hence is also not part of Other Europe). These groups/major countries are sorted by their share of global emissions.

A similar graph as Figure 1 for the groups is shown in Figure 10. While one may not want to target the entire Middle East, conversely, we may take three countries or entities out from 'Others' for early action, viz., Singapore, Hong Kong, and Taiwan. Thus, a focus on a handful of countries or groups enables us to cover almost 80 percent of global emissions.

Figure 10: Global 2019 emissions and population stacked by group or major country ordered by declining per capita emissions



Source: Fossil CO2 emissions calculated using BP data for emissions, and World Bank data for population.
Notes: The groupings are explained above, and detailed in Table 3.

Countries have limited options for reducing emissions. By definition, the framework in the paper (calculating for "N" years) keeps countries in budget if they haven't already exhausted their time (i.e., have a negative "N"). In reality, we don't know how countries or groups will perform, and thus can only compare future emissions parametrically.

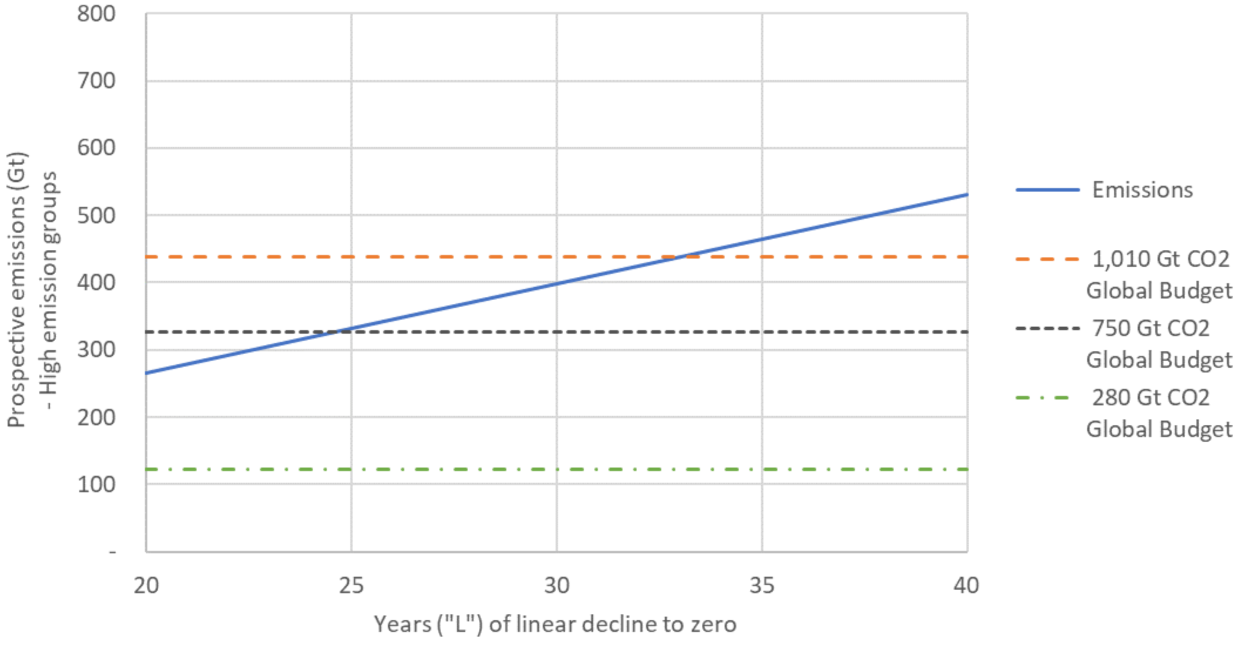
For the area-under-the-curve framework, the time to decline to zero linearly ("L") is 30 years, for both consistency and practicality. If a country is busting its budget (as is the case with groups with above-average emissions), then it could aim to come down to zero more rapidly.

For low emission countries, there are three ways of controlling emissions. First, they could shorten the time "N" until they peak and decline. Second, they could lower the rate "r" at which they can continue to grow emissions (growth is inevitable because of their low base). Third, like countries with above-average emissions, they can also decline to zero at a quicker pace instead of taking 30 years of linear decline ("L" years). Speedy declines are particularly difficult for these low-emitters as they are likely to have new infrastructure buildouts that need to be amortised, that too with a lower GDP base.

There are few options for staying within the 1.5°C rise global CO2 budget. Above average emitters would bust their budget even if they only took 25 years to come to zero. Below average emitters would also have very limited time to peak to stay in budget.

If the target is to keep future emissions within 280 Gt of remaining fossil CO2 emissions (1.5°C rise in temperature), there are, unfortunately, no visible pathways for the world to stay in budget. Allocating the remaining carbon budget between the above-average and below-average groups of countries (as in Table 3), the respective budgets would be at 122 Gt and 158 Gt CO2, respectively. The cumulative emissions for the above-average group (Figure 11) shows that even if they take only 20 years to decline to zero, they won't stay in the 1.5°C budget. The situation doesn't improve much even after allocating a bigger budget to them under the claim of 'inertia'.

Figure 11: Prospective total emissions (Gt fossil CO2) for above average emitters when declining to zero immediately ("N" = 0)

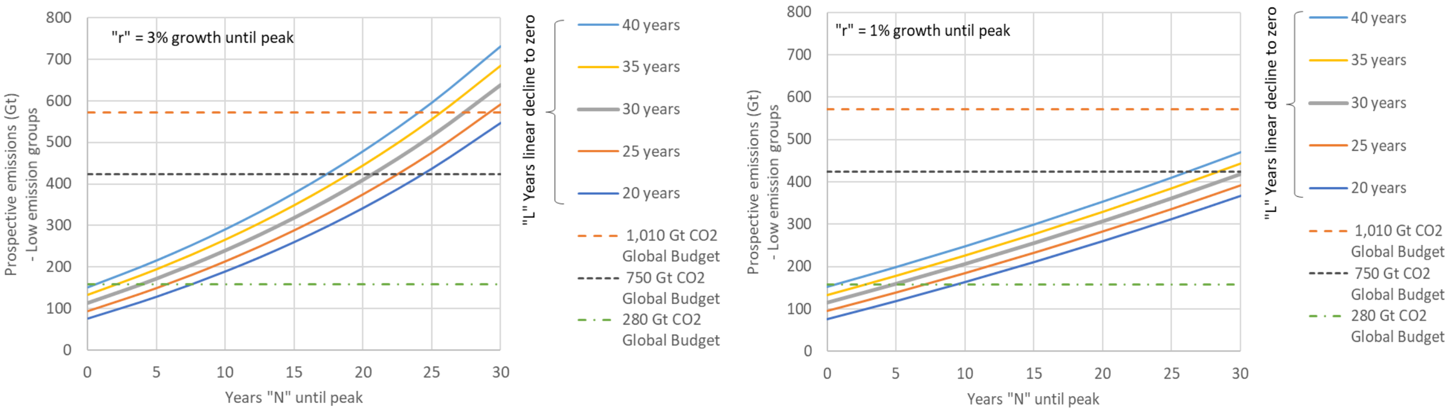


Notes: The horizontal lines are the pro-rata budgets for these eight countries or groups with above-average emissions for 2°C (50 percent confidence), 2°C (66 percent confidence), and 1.5°C (50 percent confidence), respectively. The base comparison in this paper assumed 30 years for a linear decline to zero.

These emissions assume that the eight major countries or groups decline to zero in the time listed. The calculation for the above-average emission groups assumes that even China and the US will achieve zero emissions in 30 years. However, there is no clarity on US plans for 2050. China has already declared it will take 40 years to reach zero. There are few details on their peaking plans or the emissions trajectory. By continuing 10 years beyond a 30-year decline, if we use the framework in this paper for calculation's sake, China alone will add almost 50 Gt of additional emissions. As a result, these groups bust even the budget for the highest temperature rise of 2°C rise!

For low-emitting groups or major countries, the global budget of 280 Gt CO2 would constrain them heavily. Comparing different timelines for "N" (growth until peak) and then years "L" of linear decline to zero (Figure 12), these low-emitting groups have to zero out in just a little over 30 years (adding "N" plus "L") to stay within the strictest pro-rata budget (158 Gt CO2). Lowering the growth rate to 1 percent doesn't help much – it only helps when there is time until one has to peak, which is the case for 2°C temperature rises.

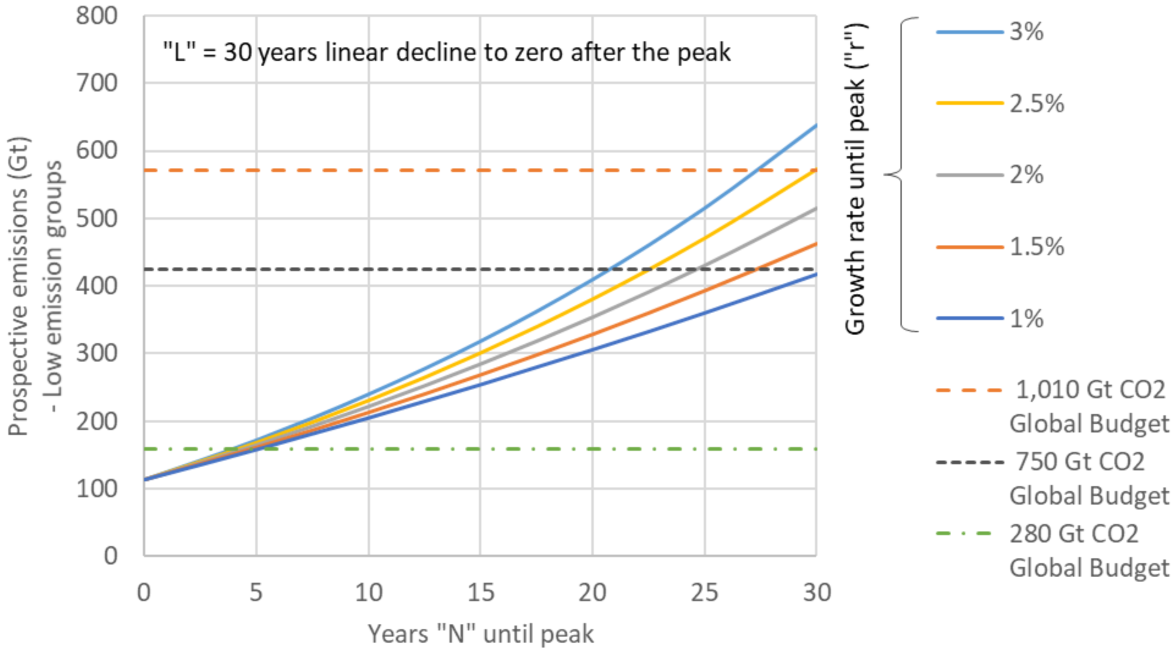
Figure 12: Prospective emissions (Gt fossil CO2) for below-average emitting groups with continued growth at (a) 3 percent until peak; (b) 1 percent until peak



Notes: The horizontal lines are the pro-rata budgets for these below-average emissions groups for 2°C (50 percent confidence), 2°C (66 percent confidence), and 1.5°C (50 percent confidence), respectively. (a) and (b) are respectively with different growth rates "r" until the peak.

In practice, there will be interplay between these instruments or choices. If a country aims for a shorter decline to zero ("L" linear years), it might have a more years ("N") until peaking. If we consider the impact of "r", keeping years to zero linear decline at 30 years (Figure 13), it is only pronounced for scenarios of high "N" (years until peaking).

Figure 13: Prospective emissions (Gt fossil CO2) for below-average emitting groups with varying growth rates and time "N" until peaking



Notes: The horizontal lines are the pro-rata budgets for these below-average emissions groups for 2°C (50 percent confidence), 2°C (66 percent confidence), and 1.5°C (50 percent confidence), respectively. This assumes the standard 30 years of linear decline ("L") to zero.

For the 1.5°C budget, in most scenarios, country groups with above-average emissions bust their budget *multiple times* more than country groups with below-average emissions

While most scenarios find both groups busting their budgets for a 1.5°C rise, it's worth emphasizing that above-average emission groups of countries bust their budget *multiple times* more than below-average groups of countries.

These figures are totals for all the groups of countries who are below average emission. Table 4 shows how each respective group fares in prospective emissions compared to their respective pro-rata budget for staying within a 2°C rise (50% confidence) with 3% growth until peak and L=30 years linear decline. As expected, we find wide variance for countries compared to their budgets. Some groups don't come close to exhausting their budget even with 30 years of growth, and the country level heterogeneity within groups is also high. Note that even this high global budget is insufficient for above average emission groups when we update their values for China and the US taking more than 30 years.

Table 4: Prospective Emissions (Gt) *remaining compared to budget* (pro-rata shares for 2°C max rise with 50% confidence) for below-average emitting groups

"N" Years of as-is at rate "r"	0	5	10	15	20	25	30
India	141.7	122.6	100.4	74.8	45.0	10.6	-29.4
Brazil	21.0	17.6	13.7	9.1	3.8	-2.3	-9.4
Indonesia	25.9	21.1	15.4	8.9	1.3	-7.5	-17.7
North Africa	18.5	14.7	10.2	5.0	-1.0	-7.9	-16.0
Other Sub-Saharan Africa	132.6	130.1	127.1	123.7	119.8	115.2	109.9
Other South and Central America	22.1	17.4	11.8	5.4	-2.0	-10.7	-20.7
Other South Asia	47.6	45.0	42.1	38.7	34.8	30.2	24.9
Other	47.5	30.0	9.8	-13.7	-40.9	-72.5	-109.0
Total below-average groups	456.9	398.4	330.6	252	160.8	55.12	-67.39

Notes: A negative number means the country or groups is busting the pro-rata budget. This assumes that "L"=30 years of linear decline to zero after the peak, and the annual growth of emissions until the peak is 3 percent. The total fossil CO2 budget for these groups is 571 Gt. The Other group has wide heterogeneity; removing Singapore, Hong Kong, and Taiwan from this group would improve its staying within budget significantly.

Barring global effort, coordination, and political will, and, perhaps, technological breakthroughs, we are on track to bust our budgets. Let's assume there are two countries that must reach zero emissions by 31 years from now ("N"=1) and 44 years from now ("N"=14), respectively. If they each fall short by two years, the over-emission by the higher emitter is *much* higher than the over-emission from the low-emitter. Using a simple year-of-zero figure doesn't highlight this disparity. We will need to plan for how to handle asymmetric emissions, both relative to budgets and in absolute terms. We revisit this issue in the section on carbon-pricing.

Limitations of carbon removal and other exotic solutions

If we can't control our emissions to stay in budget, can we remove carbon from the atmosphere or find ways to change the impact of emissions on temperature rise? One contentious option being debated at the highest global levels (Tellefson, 2019), is the use of geo-engineering. This involves the dispersion of aerosols that increase the reflectivity (albedo) of incoming energy, which would change the carbon budget available for a chosen maximum temperature rise. This has both scientific risks and geopolitical implications (e.g., what can or should a country be allowed to do unilaterally?). Even if it does 'work', this becomes a near-perpetual mandate upon mankind, because if you stop, then temperatures can rise sharply.

Over-emitters—typically richer countries—are the ones who should pay the premium for early deployment of advanced technologies such as green hydrogen, CCS, etc., and even direct air capture as required

If or when we break the global carbon budget and need to undertake heroic (and expensive) measures such as direct air carbon capture, the first countries that do so should be those who have over-emitted cumulatively, including in the past and prior to the 'date of agreement' (which, in this framework, is from when the remaining CO2 budget is apportioned). *After all, in the future, all emissions are historical*. Additionally, these countries are also almost always the ones who can afford it.

Post-combustion removal of carbon dioxide instead of emitting it is more scientifically accepted than geoengineering but still economically challenging. This is termed carbon capture and sequestration

(CCS).[16] CCS can be considered at a project or power plant level, and reduces emissions. However, for a country to remove aggregate over-emission, it needs to undertake direct air capture and removal. This is a nascent and expensive technology.

While comparing the economics of these technologies is tricky due to vast uncertainty, the framework in this paper provides a tool for examining the relative scale for direct air capture of carbon. If we assume that almost no country is able to sustain reduction greater than 3.33 percent annually for 30 years (a few of the more aggressive net-zero announcements reflect earlier peaking), then a number of countries would bust the budget. This is assuming they do decline to zero in 30 years, which is itself a big unknown. If we quantify the over-emission until reaching zero versus the prospective budget, we can compare that with current annual emissions.

The timeline for removing excess emissions becomes a fundamental issue. If we assume that they have to be removed by the time to zero emissions (say, 30 years), then we have at most 30 years for removal.[17] But beginning now is an expensive proposition, while the technologies are still improving rapidly. On the other hand, waiting for improvements along the learning curve means a reduction of time available. Any installed technology would need to be amortized over a longer time period (ideally, until its end of life) to minimize costs. This is a fundamental trade-off and an unknown.

Table 5 shows the relative scale of required direct air removal required by over-emitters compared to present annual emissions. This is for a range of timeframes of annual removal (Table 5, for 1.5°C rise, or 280 Gt fossil CO2 global budget). Taking 30 years is easiest, but the technologies are not yet cost-effective. Even with 30 years, for many countries it takes a significant fraction of present emissions to be removed annually.

[16] CCS is also termed CCUS – carbon capture, utilization, and sequestration. Most current CCUS projects use CO2 for enhanced oil recovery by oil companies.

[17] There are models to limit temperature rise that rely on removal of CO2 in the future after, say, 2050, but such scenarios of emissions trajectories lead to a higher peak temperature followed by a temperature decline. The interplay of timings versus levels of negative emissions, combined with how much over-emission happens, leads to a range of CO2 concentration trajectories, which can differ from the IPCC's representative concentration pathways (RCPs); more details on these issues are in Rogelj (2019). Table 5 and Table 6 are still accurate even if the removal period is after 2050 instead of by 2050.

Table 5: Ratio of annual removal of excess emissions versis 2019 annual emissions (1.5°C = 280 Gt global CO2 budget, 50 percent confidence)

Time to remove 30-year excess emissions →	**5 Years**	**10 Years**	**15 Years**	**20 Years**	**25 Years**	**30 Years**
UAE	2.75	1.37	0.92	0.69	0.55	0.46
USA	2.52	1.26	0.84	0.63	0.50	0.42
Canada	2.51	1.26	0.84	0.63	0.50	0.42
Russia	2.31	1.15	0.77	0.58	0.46	0.38
Japan	2.18	1.09	0.73	0.55	0.44	0.36
S. Africa	2.11	1.06	0.70	0.53	0.42	0.35
Germany	2.11	1.06	0.70	0.53	0.42	0.35
China	1.94	0.97	0.65	0.49	0.39	0.32
WORLD	1.36	0.68	0.45	0.34	0.27	0.23
UK	1.73	0.87	0.58	0.43	0.35	0.29
France	1.42	0.71	0.47	0.36	0.28	0.24
Bangladesh	Within budget					
India						
Brazil						

Notes: Excess emissions happen because we assume countries take 30 years to decline to zero, and high emitters cannot do better (or at least enough). Given they have a negative "N", they over-emit.
Countries are ordered as per their solution to "N" for 2°C rise, the same as is used in Table 2.

Table 6 shows the same calculations for the weakest target of 2°C rise (with 50 percent confidence). The situation improves, but only some countries come close to a manageable level. For others, their excess emissions are so high they still need an unprecedented scale of effort to stay in budget.

Table 6: Ratio of annual removal of excess emissions versus 2019 annual emissions (2°C rise = 1,010 Gt global CO2 budget, 50 percent confidence)

Time to remove 30-year excess emissions →	**5 Years**	**10 Years**	**15 Years**	**20 Years**	**25 Years**	**30 Years**
UAE	2.09	1.05	0.70	0.52	0.42	0.35
USA	1.26	0.63	0.42	0.32	0.25	0.21
Canada	1.24	0.62	0.41	0.31	0.25	0.21
Russia	0.51	0.25	0.17	0.13	0.10	0.08
Japan	0.04	0.02	0.01	0.01	0.01	0.01
S. Africa	Within budget					
Germany						
China						
WORLD						
UK						
France						
Bangladesh						
India						
Brazil						

Notes: Excess emissions happen because we assume countries take 30 years to decline to zero, and high emitters cannot do better (or at least enough). Given they have a negative "N", they over-emit.
Countries are ordered as per their solution to "N" for 2°C rise, the same as is used in Table 2.

CCS appears easier for handling residual emissions, such as from industry, than relying on direct air capture of CO2 to remove excess historical emissions

The only alternative for staying in budget is a more aggressive annual decline, which will also take enormous effort. A far more likely proposition for post-emission CCUS would be to tackle the tail of emissions, perhaps for the few percent which are hard to abate (maybe up to 5 percent or 10 percent of current emissions). CCS applied to the tail of future emissions would also be cheaper than direct air capture. Even these technologies would need global research and development (R&D), innovation, and technology transfer.

Carbon pricing: Is it compatible with an area under-the-curve framework?

How you price carbon depends on the objective function – spurring clean technologies, funding the transition, or redistribution

Carbon-pricing is a tool that tackles emissions by raising the price of fossil fuels through a tax or emissions trading scheme. How you price carbon depends on the objective function. Is it meant to incentivize use of otherwise expensive clean alternatives or to generate funds for managing the transition, i.e., redistribution? If the latter is the aim, is this a domestic choice or an international obligation? Are there meant to be cross-border transfers?

There are several options for how to price carbon. The mechanism could be based on absolute emissions (i.e., per ton CO2) or be relative (compared to an emissions benchmark). If it is meant to be absolute, should this be a fixed or rising carbon price? If it is relative, should the benchmark be the global emissions average or should it be compared to the target budget for respective countries?

Most current systems and frameworks use an absolute value for emissions, which means that they focus on incremental emissions, or flow. In contrast, an area-under-the-curve framework deals with the stock of cumulative emissions, which is what the science requires. As we show below, there are equity implications of different frameworks – incremental emission pricing is unfair to poorer countries.

Challenges with setting carbon prices

Carbon-pricing can motivate countries to avoid emissions. However, the High-Level Commission on Carbon Pricing, chaired by Stiglitz and Stern (2017), points out that most prices are still too low. The Commission suggests prices would need to rise over time. It's also not clear if prices, even if they are 'high enough', would result in sufficient reductions in emissions. If we classify fossil fuel taxes, such as for petrol, as an implicit carbon tax, then India already taxes petrol at well over $100/ton-CO2.[18] The short-run elasticity to prices is even worse than longer-term possibilities, which themselves little evidence for carbon-pricing resulting in substantive incremental shifts.[19]

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[18] High petroleum taxes don't impact demand significantly because of lack of alternatives, but they do offer significant revenues to the government, which could be allocated for the energy transition. Unfortunately, as of now, this doesn't happen in India. The 'coal cess' (originally established as a 'clean energy cess'), of Rs. 400/ton of coal, is now used for the Good and Services Tax (GST) compensation fund. Ali and Tongia (2020) examine India's *implicit* carbon prices in more detail.

[19] Rafaty *et al.* (2020) estimated semi-elasticity of only 0.05 percent reduction in emissions growth per average $1/ton CO2.Lilliestamet. al (2020) found some fuel switching with carbon prices, but "no empirical evidence of its

Optimal pricing of finite resources as per the Hotelling (1931) Rule for Exhaustible Resources also indicates raising prices, but only at the rate of inflation.[20] However, all rising-prices schemas pose challenges for developing regions. The emissions from developed regions are decreasing while emissions from developing regions will only rise in the near-term (Figure 8). This means that the trend-line is positive for historical over-emitters, and worse for under-emitters. Any relief from faster GDP growth in developing regions doesn't fill the gap in affordability even by 2050.[21]

Not only is it unclear if "high enough" carbon prices will materialize to effect sufficient reductions in emission, there is a fundamental disconnect between pricing carbon and setting emissions targets or caps

The real issue isn't whether or not we price carbon high enough, but whether pricing is the right solution. If we complied with a carbon budget framework like the area-under-the-curve framework, then a carbon price would either be superfluous or simply an internal mechanism for countries to choose to effect required changes in emissions. Classical economics states that one can regulate prices and let volumes float, or let volumes be restricted and discover prices, but not both, at least not efficiently (Weitzman, 1974). A fixed carbon tax may thus be inconsistent with carbon budgets, except for raising funds or for distributional reasons. Alternatively, carbon trading markets fix volumes, with floating prices, but the benchmarks of carbon volumes for most emissions trading systems today are insufficient to meet stringent carbon budgets.

Redistribution as an incentive?

To provide developing regions an incentive to do more, Raghuram Rajan (2021) proposed a mechanism of transferring funds from developed countries to developing countries based on a carbon price. The proposed transfer is linked to whether a country is over or under the global mean of emissions. The challenge is that sufficient money is unlikely to be available for a transfer, given domestic priorities for such funds (Marron and Morris, 2016). If there is a carbon tax, a fraction of such money would be required to offset any regressive impact of a carbon price. Some funding may be required simply to create buy-in and political support for such changes. This is before considering that a nation's planners could treat such taxes as a windfall or additional revenue for general budgetary needs, as with India's "coal cess" (see Footnote 18).

effectiveness in promoting the technological change necessary for full decarbonization." For energy systems, the short-term and long-term estimates for energy elasticity to prices, globally, was estimated by Labandeira et. al (2017) as -0.21 and -0.61, respectively. For electricity, their short-term elasticity was only -0.13. If we use these values to estimate the impact of carbon prices, for coal-based electricity in India, a $40/ton-CO2 price raises electricity generator costs by around Rs. 3/kWh, but this would translate into a less than 50 percent impact on end-user (retail) prices. Thus, this carbon price might only spur a short-term electricity demand reduction of about 10 percent.

[20] The Hotelling principle maximizes current value by setting price rises equal to inflation or chosen discount rate. However, this gives rise to a dilemma. Climate change asks for low discount rates across generations so that future damages aren't discounted to overly low values in present value. On the other hand, a low rate of price rise won't increase prices enough to be meaningful, e.g., the suggested at least $40 or $50/ton CO2. The solution would be to start with very high carbon prices, which appears both politically difficult as well as out of sync with most existing pricing regimes, i.e., it would be a shock to the system.

[21] Across the coming 30 years, extrapolating from the present, typical spreads of GDP growth per capita might be perhaps 4-5 percent at most comparing developing regions with the US. This means only a 4x growth in affordability by the end, while per capita income differences today are multiple times higher than this.

Far more worrying about such mechanisms are their dynamic impacts over time. Rajan posits that such a mechanism would create incentives for developing regions to lower emissions because they would otherwise lose out on incoming transfers. As Figure 8 shows, LO emitters (those with below average emissions today) will become dominant emitters over time.

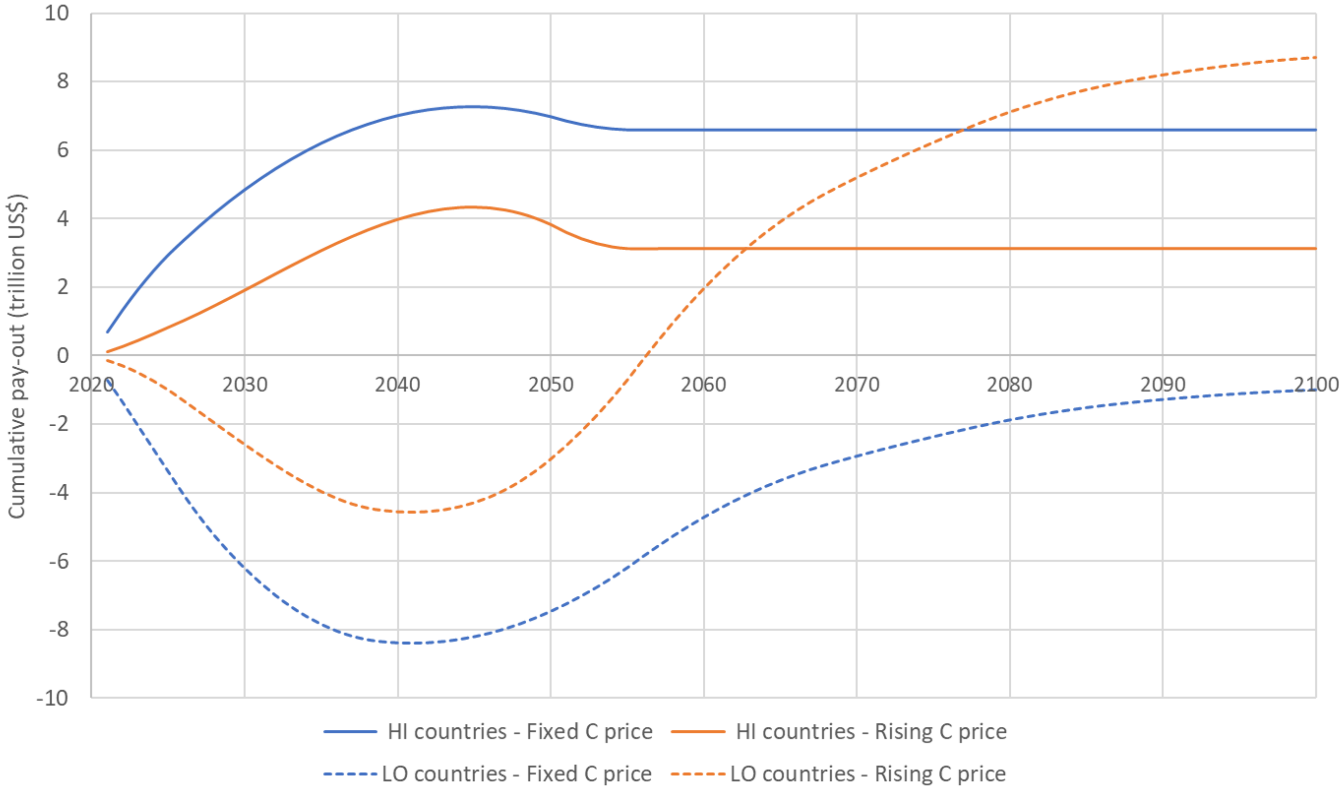
If we combined such a benchmarked framework with rising carbon prices, the picture is far worse for low emitters. To compare, let's revisit the split of countries between those over and those under the global average per capita emissions, calling them HI and LO emissions countries, respectively. We can compare calculated pay-outs versus pay-ins (Figure 14), based on whether they are above or below the global average. In theory, if the whole world stayed on track in aggregate emissions, the over-emissions (and thus carbon price pay-out) would equal under-emissions (recipients of the pay-out).

Rising carbon prices are measurably worse for low-emission countries, whose emissions are rising while emissions from high emitters are falling

However, a rising carbon price is actually worse for the LO emitters (blue lines in Figure 14). For this example, we use \$55/ton CO2 as the fixed price versus \$10 to \$100 per ton rising to the max by 2050.[22] As the fall in emissions from HI emissions countries is faster, their share of global emissions falls to the point where their per capita emissions also become below the global average. After this point, if the benchmark for pay-outs versus pay-ins is the global average, HI countries would receive payments from LO countries for a brief period of time. While one can correct for such eventualities, the larger point about how we want to benchmark emissions remains.

[22] The chosen range for rising prices has the same average as the fixed price but maxes out by 2050. Hence, when we compare the two, trends are more important than absolute values of transfers, more so since we don't know the actual future prices.

Figure 14: Cumulative carbon price pay-outs for HI and LO emitters based on fixed versus rising carbon prices (US$) referenced to the global average



Notes: The curves are based on projected emissions in the area-under-the-curve framework for a global CO2 budget of 750 Gt (2°C maximum rise with 66 percent confidence), with a three-year average of emissions rise through 2019 for estimating future emissions until the peak (except for countries which have no rise remaining to stay within budget). HI and LO countries are grouped based on whether they are above or below the global mean per capita emissions in 2019. The fixed carbon price is assumed to be $55/ton CO2, mid-way between the range for rising ($10 rising to $100/ton).

In this illustration, the pay-out is based on relative emissions compared to the country's share of global emissions over time. A negative pay-out amounts to a pay-in. This framework allows LO emitters to emit their total share in the future. Hence, using a fixed carbon price, their net pay-out approaches zero. For HI emitters, they don't revert to zero as they bust their budget.

The benchmark to average is the reason that HI emitters begin to have annual negative pay-outs (meaning pay-ins) for a few years as they lower emissions below the global average. Rising carbon prices are good for HI emitters, and worse for LO emitters.

It's important to recognise that the pay-outs and pay-ins aren't always symmetric. In the case of fixed prices, the net cumulative pay-out from HI emitters reflects the busting of their budget. This could thus be a framework for global transfers rather than simply pricing carbon emission, which as Figure 8 shows, is on a downward trend for high emitters.

Carbon prices and equity implications

Claims of 'all carbon is equal' ignore historical emissions, and also fail to factor in differential carbon marginal abatement costs

One important claim that is often repeated as a justification for even poorer countries to pay: all carbon is equal. If this is true, then we should not ignore historical emissions. The framework in this paper allocates carbon based only on prospective emissions and the remaining budget.

We should price carbon based on emissions relative to what countries *should* emit. If we apply the principles of carrying capacity for environmental regulations[23] (or even consider how initial allocations can be awarded in market-based emissions trading schemes), there is a strong argument for no-cost emissions for a subset of stakeholders even going forward. This is before factoring in affordability and the fact that the use of fossil fuels may have powered some of the GDP growth in developed countries. Claims of "free rider" effects by low emitting developing countries focus on marginal emissions by countries on an annual basis, instead of focusing on the impact of emissions on a chosen threshold carbon budget. To keep the world in budget, for every over-emission, someone else has to emit less. We've already noted that a country's tail of carbon emissions costs much more to abate.

There are a number of thorny social, economic, political, and geopolitical points of contention when it comes to climate change. For both frameworks—simple 'net-zero' and the area-under-the-curve—these translate to how much a country should emit. Do allocations or apportionments only set ambitions or do they set up benchmarks for financial liabilities (negative or positive)? What happens if a country chooses a metric—which they can do unilaterally post Paris COP21—that doesn't align with global expectations or needs?

Let's assume we bust our global budget, perhaps due to some countries more than others. Say a certain country had a budget of 100 and emitted only 75. It should be rewarded. But if we price carbon based on absolute emissions, it's still paying three-quarters of the total. This amounts to a weak relative benefit. Pricing carbon is one instrument for change but busting the budget should be linked to global financial transfers. If we base the price on tons of CO2 in excess of the budget, not on absolute tons of CO2 emitted, it would need to be higher because fewer countries would be paying. This is fair as these countries are disproportionately to blame for busting the budget, which recognizes total emissions, not just marginal emissions. *If* one wanted payments for absolute $/ton CO2, they should include historical carbon, not just prospective carbon. As Appendix 5 on equity issues shows, even ignoring emissions from the distant past and focusing on those post 1990, the excess emissions by HI emitters are worth trillions of dollars. They are unlikely to be incorporated in global consensus.

What should countries do?

All countries must spell out their emissions trajectories (not just date of zero) and what, if any, offsets are envisaged

Countries may want to announce net-zero pledges not merely for global announcements but also to galvanise stakeholders. However, such announcements should be backed by deep analysis on credible pathways to get there, not merely virtue signalling. 'Aim for the stars and you'll reach the moon' can lead to distortions, crowd out

[23] Carrying capacity assumes an equilibrium level of resource use or population (Hixon, 2008), while net carbon emissions might have a near-zero carrying capacity. However, the model of a finite temperature rise itself means we are not achieving zero emissions, and thus are working with a budget, analogous to a pseudo-carrying capacity.

alternatives, and also hurt the poor disproportionately. As Rogelj (2021a) points out, two specifics that all countries should spell out include how quickly emissions will go down (the shapes of the trajectories), and what, if any, offsets are envisaged.

For developing regions, there is an urgent need to decouple emissions from GDP growth. Such a lowering of the rate of growth of emissions in the curve would lower the peak and also cumulative emissions. Enhancing access to electricity is also critical not merely because of the human development benefits but also because electricity is one of the easiest sectors to decarbonize. The end-user doesn't even need to do much – the supply mix can and will evolve.

Developing countries need to decouple emissions from GDP growth and also focus on universal electricity service

Carbon transfers between countries shouldn't be allowed, at least not for national accounting, because these price carbon the same at different points of the emissions-reduction curve. The premium for true-zero solutions such as green hydrogen or carbon capture should first be paid by the high emitters. By flattening their curve, developing regions can benefit from global innovation and early adopters paying down learning curve costs.[24]Use of carbon credits does help avoid future emissions growth, but these don't avoid existing emissions. At a minimum, these should be accounted separately from national accounting.

While we don't want transfers of carbon accounting, we do need global finance and other support from developed countries to lower emissions growth rates in developing countries, whose domestic savings rates are nowhere near sufficient. A lower growth ("r") could be used to lower cumulative emissions from low-emitters, instead of just buying them more time with the same emissions. For this, existing technologies and business-as-usual (BAU) planning also won't suffice.

Electricity represents a large fraction of energy in developing regions and is already rapidly decarbonising. The real challenge is for industrial decarbonisation which not only requires significant investment but also lacks cost-effective alternatives (Gross, 2021). Not only are the temperatures electricity can provide insufficient for many industrial processes, there is also a chemical use of fossil fuels or release of CO_2 in many processes, especially for steel, cement, and fertilizer production.

Fossil fuel choices

All countries must plan for development pathways that avoid fossil fuel lock-ins to the extent feasible. A tough question arises over whether a country wants to embrace natural gas as a bridge fuel. On one hand, it could displace coal, but, on the other hand, it could also delay the shift to even cleaner (zero emissions) technologies. There is also the disproportionate global warming impact of methane from production and transportation leakages. This calculus isn't easy given extreme uncertainty in price points of clean (and fossil) technologies. Tongia (2021a) shows that for India, at least for the power sector, gas offers disproportionate value as a peaker in a high-RE scenario. However, the volumes of gas required for this role are modest, and natural gas scarcely makes a dent in national emissions. For base-load use, unless there is cheap gas accessible, it is squeezed between cheap coal (as available) or increasingly cheaper RE.

[24] Such a flattening-the-curve and the entire framework in this paper keep carbon accounting within the country. This avoids the intergenerational discounting and transfer concerns Thomas Schelling (1995) voiced where countries are asked to forgo emissions today to benefit citizens of other countries in the future, citizens who may be better off than us today.

Should a developing country abandon coal? At the very least, it should aggressively plan for making clean alternatives viable. Given that phasing out of coal can take time, the focus should be twofold. First, minimize or avoid new capacity. Second, clean up existing capacity instead of wishing it away. Even if India adds no new coal power plant capacity, it still uses existing plants for some years, rather decades. Half of the country's capacity was built post-2010 (Tongia & Gross, 2019). In contrast, the average coal power plant in the US is almost 40 years old (EIA, 2017a).

The best solution in the short run would be to increase the efficiency of existing coal power plants, especially younger ones. This not only lowers fuel use and carbon emissions, but also lowers local air pollution, which is a pressing challenge. As this paper shows, there is a small window ahead for below-average emitters to continue using fossil-fuel technologies.

Unfortunately, most global financiers and stakeholders have said they don't want to have anything to do with coal, even if the support could have been used to clean up existing coal. At the same time, they continue to fund oil and gas heavily, including the traditional (internal combustion) automobile industry.

Not only do global companies produce carbon-emitting vehicles, they often produce explicitly oversized vehicles like SUVs and so-termed 'light trucks'.[25] Any claims that this is what the people want are specious given the marketing push for such vehicles. A Morgan Stanley (2020) estimate for both GM and Ford shows the overwhelming majority of their profits come from such consumer trucks and SUVs.[26]

The share of sales for these 'light trucks' is high in the US. Not only are the vehicles large, their engines are oversized for the vehicle size. If the US average non-commercial-use fleet of such SUVs and light trucks were similar engine-sized as Western Europe, or, rather, just 10% more fuel efficient, this would save about four times the carbon emissions we illustrated for the 1 billion people who need electricity, even if they were supplied entirely coal-based electricity.

Going forward, while RE can meet much of incremental electricity demand, storage technologies must improve to avoid all incremental fossil fuels. Having RE displace existing fossil assets is a higher hurdle rate. It could only be possible if someone was willing to buy out such assets or until the cost of new RE plus storage exceeded the marginal costs of fossil fuel systems.[27] Such a buyout could be part of Just Transition global transfers, especially from over-emitters. Minimizing must remain the first step, followed by avoidance of new fossil infrastructure, which lowers the growth rate for the first portion of the emissions curve (Figure 3).

The scale of the effort required to bring emissions declines to even 3.33 percent annually is unprecedented. To hit this target for the world while simultaneously allowing some growth for low-emitters would require above-average emitters to be even more aggressive in their zero dates.

[25] US regulations, including fuel efficiency standards, are looser for 'light trucks' than for passenger vehicles. 'Light trucks' includes many SUVs, minivans, etc. – any vehicle with the underpinnings of trucks, such as chassis design. More details are at EIA (2017b).

[26] For example, for Ford, four out of five of their top sellers are 'light trucks' and the fifth is a loss-making compact vehicle. Out of 47 models sold globally, the top four (which are trucks) account for 43 percent of revenues and 101 percent of automotive operating income. Excluding the sub-compact Ford Focus, "the top four by revenue account for 120 percent of its global profit" (as reported by Jerry Hirsch (2020) from the Morgan Stanley report).

[27] This is before considering the fiscal implications of ending fossil fuels, which are heavily taxed in many countries, especially for petroleum products.

For developing regions cleaner energy solutions need not only sufficient capital but also low interest-rate capital. The world is awash in capital, to the extent that a number of sovereign or pension funds are happy with near-zero rates of return. However, there are multiple reasons they don't invest sufficiently in clean energy solutions in developing countries. There is the obvious concern over foreign exchange risks – where today's hedging costs at market rates use up most of the differential. A significant finance challenge is counterparty risk. Before such funds worry about returns, they worry about governance and predictability. It will take time to improve risk profiles. Countries should innovate financing and risk pooling mechanisms to help solve some of these concerns.

Ultimately, if there still is a viability gap for clean technologies, low-emitters will need transfers (grants, not loans) to help them reduce their future emissions. Such transfers could be linked to how much a high-emitter busts its budget based on the area-under-the-curve framework.

Low-emissions countries shouldn't take "not my fault" to mean "not my problem"; the impact of climate change will be disproportionate on the poor, especially in coastal countries and agrarian societies

The good news for many developing countries is that they have some remaining carbon space to allow a limited use of fossil fuels. High GDP and human development growth should be planned with the lowest rise in emissions. With such a lens, they need to revisit their choices to ask if their carbon space should be used up by elites within their country, who may drive outsized SUVs and consume more electricity than their peers in developed countries? As a corollary, low-emissions countries shouldn't take "not my fault" to mean "not my problem". The impact of climate change will be disproportionate on the poor, especially in coastal countries and agrarian societies.

A broader focus across the world, but more so for developing regions, should be on creating frameworks that enable cleaner energy systems. These include ending distortions, especially ones with implicit or explicit subsidies to the fossil sector. They should also value nimbleness in supply systems, especially a more dynamic power sector that will have to absorb high levels of RE. These improvements can be complemented with finding co-benefits from decarbonisation, such as improved local air quality, employment, and energy security. The health impacts are highest if we use RE to displace coal, which applies more in some countries than others, but even globally the net benefits are strongly positive (Scovronick *et al.*, 2019). Ultimately, market reforms will help bring in new players, innovation, and global capital.

As this paper shows, there is inconsistency in net-zero targets. If a country has a net-zero target and claims this is their contribution, Figure 5 helps us understand where in the spectrum of emissions compatible to temperature rises of, say, 1.5°C vs 2°C this falls. For many high emitters, they would, at best, come within 2°C. But then the same target should be allowed for developing region low emitters. Otherwise, this creates a divide between targets and outcomes. This holds true even before considering affordability or historical emissions.

For each ton of carbon avoided, the cheapest option may be new infrastructure in developing regions – but they should be the beneficiaries of such avoided carbon

The lowest hanging fruit, globally, is future infrastructure plans. This is disproportionately an opportunity in developing regions where new infrastructure development is upcoming. This may help these countries over-achieve carbon reductions, but they should get the credit for the same. They should also have as much flexibility as required to achieve lower cumulative emissions.

What should a country like India do?

India is unique because of its size and scale. It also relies heavily on coal (Table 8 in Appendix 2).

However, like other developing regions it should:

1. Work towards a zero-emissions commitment, while enabling that with bottom-up analysis with sector-wise plans, combined with sub-national efforts (all the more critical as electricity is both a state and federal subject in the constitution). This could then lead to peak emissions plans as well, beginning with plans for selected sectors.
2. Focus on the electricity sector, which is relatively easier to decarbonize. This includes electrification of many applications (transport, industry, cooking, etc.) and plans to cap and draw down the use of coal power plants. This begins with a plan to peak *capacity* of coal power plants.
3. Mandate—and provide finance for—ultra-energy-efficient solutions (especially ones at a systems level), and smart, nimble, and resilient energy systems. This will be vital because of the scale of upcoming development (new housing, appliances, mobility systems, etc.)
4. Demand global support—financial and technological—which could be in the form of viability gap funding. This must be true incremental support, not merely debt funding or support for RE projects which are now simply BAU.

There is a possibility for two sets of targets – one, a binding, internally-driven commitment and a second, much more ambitious plan conditional on global support. This paper shows India can continue 'as-is' for over two decades, with over 3 percent annual growth and still stay in the pro-rata budget for 2°C temperature rise. Thus, India could examine the possibility of an economy-wide peak between 2040 and 2045, and zero emissions around 2075. This matches its area-under-the-curve cumulative budgeted emissions for a 2°C rise (50 percent confidence). It could also target a more aggressive reduction in cumulative emissions—*which doesn't inherently mean earlier zero*—if it gets global support. For example, ending new coal power plants depends on cheap RE plus storage.

If India targets a sustained average 6 percent GDP growth, in theory this translates to 4 percent carbon rise today (based on its Paris pledge of emissions intensity improvement at roughly a third). The first aim should be to further improve its emissions to GDP intensity.

An area-under-the-curve framework shows that a simple net-zero target is an attractive instrument for over-emitters. It masks their excess CO2 emissions. The high-emitters must certainly commit to net-zero plans, but they need to do better. Conversely, pushing low-emitters to reach zero early is premature and unfair, and probably counter-productive. Such countries should peak as low as possible, and as soon as possible, in that order.

If we had a magic genie (or a global czar) in charge of climate change, they would probably not focus on date of zero or even carbon price. Emissions, specifically, cumulative emissions, are the only thing that matter. This paper shows a consistent framework for comparing ambitions of countries aligned with carbon budgets, with an opportunity for some to flatten-the-curve – to lower total emissions and/or achieve lower costs of emissions reductions. This framework can be refined over time with country-specific plans for emissions trajectories as these become available. Only a cumulative emissions framework will keep temperature rise under control, and also help sharpen clarity on what a country *could* and *should* be doing.

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Appendix 1: Allocation or Apportionment of Carbon Budgets

The fundamental question most studies or proposals grapple with is how do we allocate the remaining budget 'fairly'? There is a spectrum of options, ranging from ones that hurt developing countries very little to others that hurt them very much. Depending on the mechanism, especially ignoring the past or acknowledging the present (Table 7), developed versus developing fare differently. If "inertia" (anchoring allocations based on the present) is important for high-emitters, then inertia for low-emitters means they cannot grow emissions—and hence develop—rapidly, and so they would need more time to continue to grow emissions. This paper chooses the intermediate mechanism highlighted with the red oval – ignoring historical accumulation of emissions and allocating based only population share. This level of intermediate happens to be generous to rich countries by ignoring affordability (discussed below).

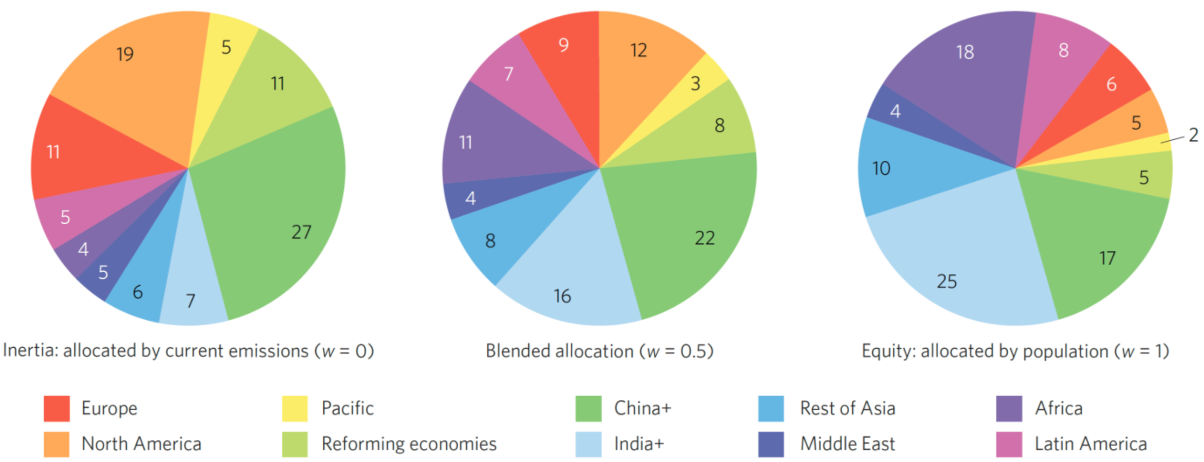
Table 7: Frameworks for allocation of carbon allocation and their impact on developing regions

	Base C budgets on cumulative emissions including historical	Ignore historical emissions, and allocation only on *remaining* carbon budget
Allocation based only on remaining per capita share	BEST	INTERMEDIATE
Anchor based on current emissions	INTERMEDIATE	WORST

Notes: The "anchor" framing posits that countries cannot switch trajectories overnight, and trajectories of lowering factor in the starting point, and so high emitters end up emitting more going forward. This is equivalent to them getting a higher share of the remaining budget prospectively. These frameworks ignore affordability, which helps richer countries.

However, across all frameworks for allocating carbon budgets, there are regional differences, e.g., as seen in Figure 15. What the methodology below calls 'equity' still ignores historical emissions.

Figure 15: Comparison of sharing the carbon quota across regions through different frameworks



Source: Figure 1 from M. Rapauch et al. (2014).

Notes: The figure allocates remaining (prospective) emissions across regions based entirely on population ('equity') versus based on existing emissions ('inertia'), or a linear combination.

Low-emission countries are under no obligation to accept blending with inertia at all, let alone blending at a 0.5 ratio. Inertia is simply allocation based on current emissions, which are highly skewed. By definition, 'inertia' means continuing, or at least encouraging, current trajectories, which is precisely what we aim to avoid.

Nicole J. van den Berg, *et al.* (2020) compare a range of apportionment techniques, ranging from grandfathering (called "inertia" above) to per capita allocations (the base in this paper), cumulative per capita (including historical), ability to pay, greenhouse development rights (to reach a minimum level of development), and cost-optimal solutions (based on marginal abatement cost (MAC) curves). They also consider blends between these methodologies. The majority of mechanisms allocate even more carbon space to poorer low-emissions countries than the base used in this paper. In particular, adding an affordability dimension significantly increases the allocation for poorer countries.

Budolfson *et al.* (2021) focus on a utilitarian benchmark for emissions and NDCs and compare this to cost-minimisation. They find utilitarian benchmarks also create a much greater apportionment skew between high and low emitters than used in this paper.

Appendix 2: The disproportional impact of phasing out coal on some countries

Any push to end coal will disproportionately impact the top ten consuming nations who use three-quarters of global coal (Table 8). But it won't hurt many of the OECD countries in the list as much because most of them use a lot of 'something else', especially oil and gas.

China uses half the world's coal, and India is the second largest consumer. However, on a per capita basis, if we also normalize coal use based on energy content (a proxy for carbon emissions), then India used half the world average coal per capita in 2019. Ending coal would hit almost half its primary energy. But for the US, which still used triple India's coal per capita in 2019, it would only impact 12 percent of primary energy, and the impact on Germany would also not be so high.

Table 8: Top coal producers and consumers 2019

	Production (million tonnes [MT])	Consumption (MT)	Per capita coal consumption (kg)	Estimated average calorific value (kcal/kg)	Converted per capita coal energy consumption (GJ)	Share of primary energy from coal
China	3,846	3,936	2,826	4,958	59	57.6%
India	756	966	714	4,021	12	47.7%
United States	640	507	1,553	5,340	35	12.0%
Germany	134	244	2,941	2,257	28	17.5%
Russia	440	174	1,202	4,991	25	12.2%
South Africa	254	161	2,789	5,655	66	70.6%
Indonesia	610	138	516	5,894	13	38.2%
Poland	112	115	6,284	3,975	105	44.7%
Kazakhstan	115	93	2,442	4,307	44	53.9%
Australia	507	69	2,751	6,199	71	27.8%
Colombia	82	9	180	6,871	5	13.4%
Rest of world	632	1,937	505	3,678	8	12.4%
Total World	8,129	7,658	1,009	4,925	21	27.0%

Source: Table 1.1 in Tongia and Sehgal (eds.) (2020), "Future of Coal in India: Smooth Transition or Bumpy Road Ahead?"

Coal and Energy data from BP Statistical Review of World Energy 2020. Consumption data in tonnes calculated from energy (exajoules as listed via respective conversion as per production data, which was listed in both energy and tonnes). Population data taken from UN (n.d.). Only Indian consumption data are as per Ministry of Coal FY2018-19 official data.

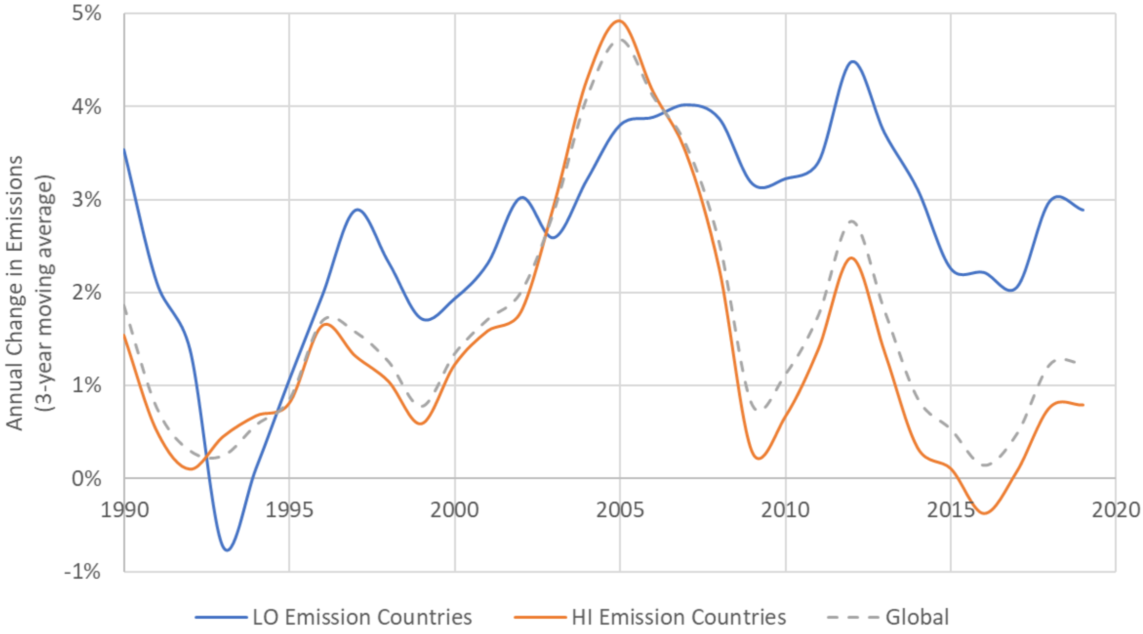
Notes: Calorific values are calculated estimates, with uncertainty due to variance in the breakdown of imported coal by calorific value. A low share of primary energy from coal suggests high carbon emissions from other sources but specific alternatives to coal vary by country.

The US and UK first reduced their use of coal because they had access to cheap natural gas, not because of Renewable Energy (RE). Going forward, the hope is that clean energy technology can fill the void created by ending coal, but RE is not yet cost-effective when we factor in storage technologies, at least not for large-scale time-shifting in developing regions.[28]

[28] Literature typically shows cheaper storage when blended with solar, but blending only applies on an energy basis, not on a capacity basis, e.g., when meeting the peak—often an evening peak—is the requirement, which also varies seasonally. Tongia (2021b) has an India-specific time of day analysis for electricity in India that highlights this difference.

Appendix 3: Trendline for HI and LO emission countries for annual emissions change (3-year moving average)

Figure 16: Trendline for HI and LO emission countries for annual emissions change (3-year moving average)



Notes: This groups countries into HI and LO emissions based on their whether they have higher than or lower than average per capita fossil CO2 emissions in 2019.We note that the global average strongly tracks the emissions of HI countries (who were 78 percent of fossil CO2 emissions in 2019). The huge rise in the mid-2000s for HI (and thus global) was dominated by China.

Appendix 4: Impact on time left as per the framework for various blends of equity vs. inertia

As a hypothetical exercise only—without judgement as to appropriateness—let us consider different blendings between these two modes of carbon budget apportionment in Appendix 1 (inertia and equity).Table 9 shows the impact of blending on this framework solving for "N" years at different ratios of equity (population) versus inertia (current emissions); (1 = fully population based, the default in the paper). The impact is highly non-linear. The absolute impact on "N" from changed apportionments is lower for the 1.5°C rise case, which is what the world should target. The table also shows the percentage change in total years until zero (thus, "N" + 30 years), compared to the base scenario of w=1. There is a strong skew – high emissions countries benefit *much* more, at the expense of low-emissions countries.

Table 9: Years "N" remaining before needing to start 30-year decline for maximum rise of 1.5°C and 2°C (50 percent probability) with different weightages of population versus present emissions, with percentage impact on time before achieving zero.

	1.5°C rise (global 280 Gt fossil CO2)			2°C rise (global 1,010 Gt fossil CO2)		
	Years "N" for w = 0.5	Years "N" for w = 0.75	Years "N" for w = 1 (paper default)	Years "N" for w = 0.5	Years "N" for w = 0.75	Years "N" for w = 1 (paper default)
	Percentage change for time until zero (N+30 years) due to apportionment weightage			*Percentage change for time until zero (N+30 years) due to apportionment weightage*		
UAE	-13.2	-16.6	-21.3	1.8	-4.6	-13.5
	94%	*54%*		*93%*	*54%*	
USA	-12.2	-14.8	-18.0	4.5	-1.1	-7.2
	48%	*27%*		*51%*	*27%*	
Canada	-12.1	-14.7	-17.9	3.5	-1.0	-7.0
	48%	*26%*		*46%*	*26%*	
Russia	-11.3	-13.3	-15.6	5.4	1.6	-2.7
	30%	*16%*		*29%*	*15%*	
Japan	-10.8	-12.5	-14.3	11.7	5.3	-0.2
	22%	*12%*		*40%*	*19%*	
S. Africa	-10.5	-12.0	-13.7	7.0	4.0	0.9
	19%	*10%*		*20%*	*10%*	
Germany	-10.5	-12.0	-13.7	39.9	15.0	2.7
	19%	*10%*		*114%*	*38%*	
China	-9.9	-11.0	-12.2	6.3	4.6	2.9
	13%	*7%*		*10%*	*5%*	
WORLD	-7.8			11.4		
UK	-9.1	-9.8	-10.5	23.1	18.7	14.7
	7%	*4%*		*19%*	*9%*	
France	-8.0	-8.1	-8.2	20.4	20.0	19.6
	1%	*0%*		*2%*	*1%*	
Bangladesh	5.3	7.8	9.9	16.6	19.7	22.1
	-12%	*-5%*		*-10%*	*-5%*	
India	-0.9	1.3	3.1	17.3	21.0	24.3
	-12%	*-5%*		*-13%*	*-6%*	
Brazil	-2.3	0.1	2.6	39.3	51.7	65.2

	-15%	*-8%*		*-27%*	*-14%*	

Notes: w = chosen share of equity (population weightage) versus inertia (2019 emissions). w=1 corresponds to equity (prospective only, ignoring historical emissions), and matches the results from the paper. The trend for extrapolation and present emissions per capita are same as per Table 2, and the countries are sorted by years remaining ("N") before peaking then declining for a 2°C maximum rise with w=1. The WORLD timeline doesn't change with different apportionments. Colour codes show negative values, for "N" and for relative difference in years until zero (thus, based on N + 30) with changing carbon apportionment from w=1 as the base.

Appendix 5: Issues of equity: should the future acknowledge the past?

Climate change is a classic externality like many forms of pollution. But it is different from many traditionally regulated pollutants because of its global scale and centuries-long timescale. If one uses fossil fuels, everyone, and not just one's own country or region, gets affected by the temperature rise and climate pattern shifts. Even worse, the most vulnerable and impacted (the Global South) are not the ones who created the challenge. On top of this, we have issues of inter-generational discounting (Schelling, 1995), given the long lifespan of greenhouse gases like CO2.

Unfortunately, at the end of the day, addressing climate change is unlikely to be 'fair'. If we agree collectively to move ahead by writing off historical emissions, this becomes a transfer from under- to over-emitters. A compromise entails choosing a relatively recent starting point for measuring emissions and apportioning the remaining carbon budget accordingly; this paper ignores *all* historical emissions as its base for apportionment.

Global recognition of carbon emissions and climate change was widespread by 1990, if not earlier. Global fossil CO2 emissions from 1990 to the present (through 2020) were 855.4 Gt,[29] not very far from the remaining global C budget (2021 onwards) for keeping temperature rises within 2°C with 50 percent probability. During this period, HI emission countries (those above the world per capita average in 2019) had over 81 percent of global emissions. US fossil CO2 emissions were 19.4 percent, despite their having only 4.5 percent of the population. Thus, its *overuse* of carbon beyond its then share was 127.8 Gt. China over-consumed 12.4 Gt, while India under-consumed 105.6 Gt, compared to its population.

If we apply a 'meaningful' carbon price of just $40/ton CO2 in current terms, this represents a transfer from under-emitters to the US of $5.1 trillion, and to China of $0.5T, by writing off just the 1990-2020 emissions. For India, they transferred out $4.2T of carbon space.

This carbon isn't coming back, and this money won't be 'returned' either. But some of it could come back through collaborative efforts. Tackling climate change will require all nations to be as aggressive as possible in lowering their emissions. Also, as and when we deploy carbon border adjustments or tariffs, the prices *as signalled* might need to be uniform to avoid leakages, but *net* cross-border financial transfers should reflect the cumulative-emissions-based values shown in this paper.

[29] This calculation uses actual emissions through 2019, and assumes 2020 is similar to 2019, even though it would be lower due to COVID-19. To adjust for this, the model also doesn't take 2021 (with its expected rebound) on actuals either, and assumes 2020 and 2021 simply smoothen out.