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Balancing climate and development goals

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Abstract
Decarbonizing the energy system is a major challenge facing the richest countries, whereas provision of energy services is a major challenge facing the poorest countries. What would be the climate consequences if only richer countries focus on decarbonization, and only poorer countries focus on provision of energy services? To address this question, we create future scenarios in which carbon dioxide (CO\textsubscript{2}) emissions increase according to a historical trend and then start to decline only when countries reach specified income levels. In our central case, we assume that when countries start to decarbonize, they reduce emissions at 2\% yr\textsuperscript{-1}. With this assumption and if all countries begin to decarbonize in 2020, the world would be expected to warm by 2.0 °C relative to pre-industrial times. If countries begin to decarbonize only when their per capita gross domestic product (GDP) exceeds $10,000, there would be less than 0.3 °C of additional warming. Yet over half the world’s population currently lives in countries below such an income threshold, and continued direct CO\textsubscript{2} emissions by people who live in these countries, while they remain underdeveloped, would increase global average temperature rise by 14% relative to the case, in which all people begin to decarbonize in 2020. The primary concern of developments driven by fossil fuels in lower income countries might relate to issues such as the technological lock-in to high-emission technologies.

1. Introduction
Carbon dioxide (CO\textsubscript{2}) emissions grew at about 1.5% yr\textsuperscript{-1} from 2008 to 2017, which can be explained mainly by growth in economic activity [1]. A number of studies have examined the nexus between economic growth and CO\textsubscript{2} emissions [2–7]. Many of them have found that economic growth increases CO\textsubscript{2} emissions, especially for emerging countries such as China, India, and Brazil [2, 5, 7], with some studies providing evidence that the carbon-intensity of economic activity is higher at early stages of development than at later stages. Decomposition of the fossil fuel and cement CO\textsubscript{2} emissions (E\textsubscript{CO\textsubscript{2}}) into a simplified Kaya identity

\[
E_{\text{CO}_2} = GDP \times I_{\text{CO}_2}
\]

expresses E\textsubscript{CO\textsubscript{2}} as the product of both gross domestic product (GDP) and CO\textsubscript{2} intensity of GDP (referred to as carbon intensity; I\textsubscript{CO\textsubscript{2}}). Here, carbon intensity incorporates both influences from energy intensity of GDP and carbon intensity of energy. Records from the World Bank show that worldwide carbon intensity I\textsubscript{CO\textsubscript{2}} has continuously decreased from year 1960 to 2000, but has remained relatively constant since 2000 (figure S1 (https://stacks.iop.org/ERL/15/124057/mmedia)). The form of Kaya identity used here does not capture the full fossil fuel dependence explicitly, nor does it represent geographic variation in carbon intensity or the mechanisms whereby countries can alter their carbon intensities. Nevertheless, this approach permits transparent analysis of the implications of assumptions. More comprehensive analysis could focus on drivers of fossil-fuel use in developing countries.

An increase in CO\textsubscript{2} emissions from economic growth could deteriorate the climate mitigation effort agreed to under the Paris climate agreement [8]. Climate models project a nearly direct relationship between cumulative CO\textsubscript{2} emissions and transient climate responses [9–15]. Studies have shown that the total cumulative CO\textsubscript{2} emissions must be limited to 3200 GtCO\textsubscript{2} (value may vary in different studies) to keep global temperature rise below 2 °C relative to...
the period of 1850 to 1900, with both CO$_2$ and non-CO$_2$ forcing and a 66% probability considered [16, 17]. About three-quarters of this budget had already been emitted by the end of 2018, leaving a remaining time scale of less than two decades at current emission rates [1]. Investments in fossil fuel infrastructure today could restrict the future flexibility of transition to a low-carbon world and preclude future decarbonization, a situation known as the carbon lock-in [18–20]. Recent analysis based on fossil-fuel-burning infrastructure records has found that committed CO$_2$ emissions from existing and proposed energy infrastructures already surpass the remaining carbon budget to stay under the 1.5 °C global warming target, and represent two-thirds of the remaining carbon budget to stay under the 2 °C warming target [21]. Thus, reducing CO$_2$ emissions enough to stay within the remaining carbon budget is a challenging goal [16, 21–23].

Worldwide energy consumption grew by ~2.3% in 2018, nearly twice the average rate of growth since 2010 [24]. Fossil fuels, including coal, natural gas, and oil, remain as the primary energy source and account for nearly 70% of the total growth in energy consumption. While there is an upward trend for countries to develop renewables to meet increasing energy demands, consumption of renewables is still limited due to factors such as the relatively high initial capital cost and technological barriers [25, 26]. This is particularly true for less developed countries, which have a relatively lower per capita income and per capita CO$_2$ emissions (figure S2). A 2019 study [27] examined relationships between energy consumption and economic activities for 107 countries, and found that a country’s choice of energy source depends substantially on its level of development. Highly developed countries, including the United States, Japan, Australia and countries in Europe, appear to be more willing to subsidize renewable energy technologies. In contrast, countries at an early stage of development tend to prioritize economic growth or poverty reduction by using relatively low-cost and easy-to-operate energy sources. Balancing development and CO$_2$ emissions for less developed countries is thus important.

In this analysis, we explore the climate consequences that would emerge when countries develop to a specific per-capita GDP level before they start reducing CO$_2$ emissions. Our aim is to demonstrate the approximate magnitude of effects of various per-capita GDP choices using a simple and transparent approach, while recognizing the deep uncertainties inherent in national scale projections out to the year 2100. We estimate future CO$_2$ emissions from economic developments using a parsimonious statistical model that considers scenarios in which countries follow a projected GDP increase, and then cut their emissions only when they get wealthier (see Methods). Country-level GDP and population projections from the Shared Socioeconomic Pathway scenarios (SSPs) [28, 29] are used with carbon intensity $I_{CO_2}$ derived from historical records. Note that our estimations rely purely on an empirical relationship between historical carbon emissions and GDP, and thus do not fully account for potential emissions locked-in by fossil fuel infrastructures, which could have long-term impacts.

2. Methods

Our analysis uses historical records of CO$_2$ emissions, GDP, and population from the World Bank [30–32]. To quantify the relationship between historical CO$_2$ emissions and GDP, we estimate the carbon intensity of GDP, $I_{CO_2}$, using data from 1961 to 2014, and assume that changes in $I_{CO_2}$ can be described as:

$$I_{CO_2} = \frac{I_0}{(1 + r)^{\text{year} - \text{year}_0}} \quad (2)$$

where $I_0$ represents the carbon intensity in the reference year ($\text{year}_0$), and $r$ shows the improvement rate in carbon intensity. We assume that changes in $I_{CO_2}$ follow historical trends. Accurate projections of future change in $I_{CO_2}$ rely on assumptions of countries’ energy efficiency, economic structure, and many other factors, many of which are difficult to predict. For the central case, we use the global-scale data and apply it to all countries. Using the least squares curve fit returns an improvement rate of global-scale carbon intensity $r = 1.09\%$ yr$^{-1}$ with $R^2 = 0.96$. We also separate all countries into low-, middle-, and high-income groups based on the World Bank income level classifications (table S1), and calculate $I_{CO_2}$ and $r$ for each income group, respectively. $r$ is 1.40% yr$^{-1}$ for the low-income ($R^2 = 0.95$) group, 0.83% yr$^{-1}$ for the middle-income ($R^2 = 0.61$) group, and 1.76% yr$^{-1}$ for the high-income ($R^2 = 0.99$) group. Further examinations show that decrease in $I_{CO_2}$ is mainly a result of decrease in energy intensity of GDP for the same period, while the carbon intensity of energy increases slightly for low- and middle-income groups (see figure S3). Here all dollar values are reported in 2010 US dollars.

To predict future CO$_2$ emissions, we make use of country-level GDP projections from the Shared Socioeconomic Pathways (SSP) scenarios [28, 29, 33]. SSP scenarios provide decadal scale GDP and population projections for 177 countries up to 2100. GDP projections for SSPs express narratives that capture different scenarios of technological progress, improvements in energy use efficiency, cross-country inequality, and human capital accumulation. In our conceptual work, we assume GDP growth contributes to CO$_2$ emissions via the carbon intensity $I_{CO_2}$ calculated from equation (1). That is, future annual carbon emissions are estimated as the product of GDP and carbon intensity at country-level and for
each year. Global-scale emissions are calculated as the sum of country-level predictions for available countries.

Our central case adopts a global-scale carbon intensity trend and is applied to all countries based on the SSP5 pathway. In the main text we consider three scenarios: for NoReduce, the carbon intensity \(I_{CO_2}\) for all countries at the beginning of projection equals the value estimated considering all countries, and evolves with a prescribed improvement rate derived from the equation (2); for AllReduce, all countries reduce their annual emissions 2% each year starting in year 2020; for 10kReduce, countries start reducing emissions 2% each year when their per capita GDP levels reach $10 000 per year. Countries that exceed this level prior to 2020 start reducing emissions at the same rate in 2020. That is, richer countries start reducing their emissions right away while poorer countries continue emitting consistent with GDP projections and carbon intensity assumptions until their per capita GDP reaches the $10 000 per year threshold. The 2% annual reduction rate implies a 25% reduction of annual CO\(_2\) emissions in \(\sim\)15 years and 50% reduction in 30 years. For the decade of 2004–2014, many countries, including the United Kingdom, France, Romania, and Ukraine, have shown a decrease in annual CO\(_2\) emissions of more than 20%. The best estimates of warming resulting from a time series of emissions would require detailed information about the CO\(_2\) redistribution among the atmosphere, land, and ocean, and climate sensitivity, which is normally obtained with the help of coupled climate models. Here, consistent with the overall aim of providing simple approximations, we estimate peak warming likely to result from an amount of cumulative CO\(_2\) emissions, following the Fifth Assessment Report of the United Nations Intergovernmental Panel on Climate Change (IPCC) [17], by being linearly proportional to a 2 °C increase in the global mean temperature per 1000 GtC (3667 GtCO\(_2\)) CO\(_2\) emitted. To account for historical emissions, 1889 GtCO\(_2\) (515 GtC) cumulative CO\(_2\) is added since 2011.

To assess the uncertainty range of estimated total CO\(_2\) emissions and corresponding global warming, we consider scenarios with a large range of the per capita GDP thresholds (0 to 80 k$/yr\(^{-1}\)), annual emissions reduction rates (0%–8% yr\(^{-1}\)), and future GDP pathways (SSP1 to SSP5). For most figures and analyses in the paper, we focus on the specific GDP threshold values (e.g. 10kReduce, 20kReduce, 40kReduce, and 80kReduce) and CO\(_2\) reduction rates (0% yr\(^{-1}\), 1% yr\(^{-1}\), 2% yr\(^{-1}\), and 4% yr\(^{-1}\)) chosen somewhat arbitrarily to span the likely range of interest. To test uncertainty related to the carbon intensity change, we use carbon intensity \(I_{CO_2}\) and carbon intensity improvement rate \(r\) derived from different income groups to replace values in the central case. We also include one case where we apply different values to countries in different income groups.

### 3. Results

Figure 1(A) shows the time series of projected per capita GDP under the SSP5 pathway and corresponding year to reach specific per capita GDP thresholds ($10 000, $20 000, $40 000, and $80 000 per year) for selected countries. These countries are chosen based on their per-capita income and total projected population in 2020, which are used to show features of countries in the low-, middle-, and high-income groups. Full list results for all available countries are included in table S2 to S5. Note that the estimates of per-capita GDP and thus year to reach specific threshold based purely on GDP and population data from SSP5 and is not affected by our assumptions. Substantial difference is shown among countries at various development stages. Compared to AllReduce, in which all countries start reducing carbon emissions in 2020, the starting time of emission reduction in 10kReduce is delayed by \(\sim\)27 years on average for the low-income group. Corresponding country-level cumulative carbon emissions between 2020 and 2100 increase slightly for these countries (figures 1(B), S4, and S5). The largest difference in the cumulative CO\(_2\) emissions between 10kReduce and AllReduce occurs in India (189 GtCO\(_2\)) because of its low initial per-capita GDP and rapid projected development. Countries that have already or are expected to reach $10 000 per capita income level by 2020 show no change in their carbon emissions in 10kReduce.

The global annual CO\(_2\) emissions increase monotonically in NoReduce from \(\sim\)41 GtCO\(_2\) yr\(^{-1}\) in 2020 to 155 GtCO\(_2\) yr\(^{-1}\) in 2100 (figure 2(A)), with an estimated total cumulative emission of about 8500 GtCO\(_2\) between 2020 and 2100 (figure S6)—substantially larger than the remaining available carbon budget to keep the world below 2 °C warming. Comparison of global scale annual CO\(_2\) emissions with that in SSP5-8.5 and RCP8.5 scenarios is shown in figure S7. For AllReduce, all countries reduce carbon emissions from 2020, leading to a continuous decrease in global annual CO\(_2\) emissions to 12 GtCO\(_2\) yr\(^{-1}\) by 2100. Between NoReduce and AllReduce, 6900 GtCO\(_2\) of cumulative emissions are avoided.

Compared to AllReduce, if countries do not start to reduce emissions until they reach the $10 000 per year per-capita GDP threshold (i.e. 10kReduce), global annual CO\(_2\) emissions in 2100 increase by 4.1 GtCO\(_2\) yr\(^{-1}\) (figure 2(A)), with an estimated increase in total cumulative CO\(_2\) emission by 539 GtCO\(_2\). This would imply an additional 2.6% of annual CO\(_2\) emissions and 6.4% of cumulative emissions compared to NoReduce (figure 2(B)). If countries wait until they reach a $20 000 per year per-capita GDP level (i.e. 20kReduce), global annual emissions in 2100
Figure 1. (A) Time series of projected per capita GDP and estimated time to reach specific per-capita GDP levels and (B) corresponding projected cumulative CO\textsubscript{2} emissions between 2020 and 2100 under various emissions reduction assumptions. For NoReduce, countries will not reduce emissions throughout the 21st century. For AllReduce, all countries start reducing their CO\textsubscript{2} emissions in 2020. A 2% yr\textsuperscript{-1} emission reduction rate is applied for all cases and GDP and population from the SSP5 scenario are used. The global-scale cumulative CO\textsubscript{2} emission increase between 10kReduce and AllReduce is only 6% compared to emissions in NoReduce between 2020 and 2100. Total emissions from the EU is also included in panel B, as the sum of estimated CO\textsubscript{2} emissions for all available countries in the EU. Results for all countries in panel A are listed in Tables S2 to S5, and results for panel B are listed in Table S7.

would increase by 8.3% associated with an additional 17.4% increase in cumulative emissions compare to NoReduce (see figure 2(B) for other GDP threshold cases). Over half the world’s population predicted in year 2020 under SSP5 pathway lives in countries with per-capita GDP < $10,000 per year, and over 80% the world’s population live in countries with per-capita GDP < $20,000 per year (figure 2(C)). This would suggest a limited impact of direct carbon emissions from participation of the majority of the world’s people, who live in less developed countries, on global scale total carbon emissions.

We estimate a corresponding increase in temperature at year 2100 based on different levels of increase in cumulative CO\textsubscript{2} emissions under SSP5, relative to the preindustrial times, for a range of GDP thresholds and emission reduction rates (figure S8). Figure 3 shows additional global warming from cumulative CO\textsubscript{2} emissions for scenarios with various per capita GDP thresholds compared with those that start mitigating from 2020. Numbers are shown in Table S6. Our central case, 10kReduce, leads to ~0.3 °C warming. Varying emission reduction rates, while fixing the per-capita threshold to $10,000 per year, produces additional warming that ranges from ~0.2 °C (8% per year) to 0.4 °C (0% per year), respectively, which suggests that (at ≤ $10,000 per capita per year) an increase in temperature is relatively insensitive to the emission reduction rate. However, varying GDP thresholds while fixing the emission reduction rate to 2% yr\textsuperscript{-1} results in an additional warming up to ~1.6 °C for 40kReduce and 2.7 °C for 80kReduce. This
implies that if middle-income countries do not participate in emissions reductions, high-income countries would need to decarbonize at an extremely rapid rate to keep Earth’s atmosphere within a reasonable warming level.

Further evaluations of uncertainty associated with estimated global warming are shown in figure S9, which consider cases with a large range of per capita GDP thresholds, emissions reduction rates, future projection of GDP developments, and the carbon intensities and its improvement rate (see Methods). For low per-capita income threshold scenarios ($\leq $10 000 per year per capita), the uncertainty range of estimated warming is small across all possible scenarios considered here, whereas the higher per-capita thresholds ($> $10 000 per year per capita) would lead to substantially larger uncertainties in future warming. Our results thus indicate that future CO$_2$ emissions and the corresponding global mean warming are relatively insensitive to other factors when compared to GDP threshold, and suggest an early attempt to mitigate CO$_2$ emissions would increase confidence in mitigation outcomes.

4. Discussion

No one can foresee how the 21st century will unfold with any degree of specificity and confidence. Our goal is to provide a transparent calculation to inform discussions. Detailed quantitative analysis calls for further investigations using sophisticated models based on adequate assumptions. For example, considerations of other types of GHGs and relatively active aerosols may affect our results quantitatively. The predicted annual CO$_2$ emissions in our NoReduce case is close to that provided in the SSP5-8.5 scenario and slightly larger than that in the RCP8.5 case, noting that some studies deem the RCP8.5 case to be unrealistically high [34]. Nonetheless, we have shown that across a wide range of scenarios and assumptions a delay by poorer countries in joining the decarbonization trends, assuming that countries shift to reduce emissions when they reach some specified level of prosperity, will have only a modest effect (while still important when considering 2 °C warming goal) on total cumulative CO$_2$ emissions, compared to consequences that would happen if more developed
Figure 3. Additional global mean warming in various emission reduction scenarios at year 2100 compared to scenarios in which countries reduce emissions starting in 2020, as a function of per-capita GDP threshold and emissions reduction rates. The x-axis shows the percentage of global population projected in 2020 under various per-capita GDP levels. Lack of participation by countries with GDP < $10,000 per year (containing over half the world’s population) would increase global mean temperature by ∼ 0.3 °C. However, lack of participation of middle-income countries would substantially increase the global mean temperature.

countries delay in joining the decarbonization process.

Greater concerns about the use of fossil fuel energy sources for less developed countries may relate to their ability to decarbonize as their wealth increases; as we have identified, the direct carbon emissions from lower income countries, while their incomes remain lower, will have a limited climate impact. The primary issue associated with the use of fossil fuel infrastructure may lie in aspects such as technological lock-in to high emission technologies. Many former colonies remain locked into driving on the same side of road or using the same kind of electrical outlet as their former colonizers did, despite few devices having survived from colonial times. Previous studies have shown the crucial role of energy investments in the next few decades [18, 35]. The long lifetime and relatively high capital cost of energy infrastructure could delay carbon mitigation actions and lock the global economy into a carbon-intensive system. This suggests that the most climate-effective focus on less developed countries would be on near-term energy provision while also minimizing long-term carbon lock-in to a CO₂-intense system. Overcoming the lock-in will ultimately require regulations that stipulate emission reductions from specific technologies or sectors; targeted financial incentives to encourage decarbonization; or removal of implicit or explicit subsidies for the high-carbon systems.

Our analysis does not consider other issues such as the inequality within each country, which could have implications on future CO₂ emissions. To effectively assess the relative costs and benefits associated with different climate policies, factors such as environmental degradation, including air pollution and water risks and impacts on human health also figure into the equation [36, 37]. These elements are beyond the scope of this study.

Using an extremely simple model, we have examined the climate implications involved when less developed countries prioritize development goals over climate goals while they remain underdeveloped. The assumptions considered in our analysis are simple and transparent. Our results highlight implications of a continuance in historical trends in global-scale carbon intensity, coupled with GDP projections under SSP scenarios. They indicate that if countries with a per-capita GDP less than $10,000 per year develop consistent with the global-scale historical trends, while countries above that GDP level reduce emissions at a rate of 2% yr⁻¹, the lack of participation of less developed countries would add only an estimated 6% to the total cumulative CO₂ emissions between 2020 and 2100. While more comprehensive models may produce different quantitative results, the fundamental qualitative conclusion is likely to be true: compared to risks for more developed countries not participating in decarbonization process, there is a relatively modest impact on global temperature change if less developed countries do not mitigate their CO₂ emissions immediately, but begin to mitigate when they become wealthier. For this to be true, however, long-term technological lock-in to emitting technologies must be avoided.
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Data availability statement

The data that support the findings of this study are openly available at the following URL: https://github.com/LDuan3008/Balancing_development_emissions_2020.

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