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The Climate Implications of Ending Global Poverty

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Abstract

Previous studies have explored potential conflicts between ending poverty and limiting global warming, by focusing on the carbon emissions of the world's poorest. This paper instead focuses on economic growth as the driver of poverty alleviation and estimates the emissions associated with the growth needed to eradicate poverty. With this framing, eradicating poverty requires not only increasing the consumption of poor people, but also the consumption of non-poor people in poor countries. Even in this more pessimistic framing, the global emissions increase associated with eradicating extreme poverty is small, at 2.37 gigatonnes of equivalent carbon dioxide in 2050, or 4.9 percent of 2019 global emissions. These additional emissions would not materially affect the global climate change challenge: global emissions would need to be reduced by 2.08 gigatonnes of equivalent carbon dioxide per year, instead of the 2.0 gigatonnes of equivalent carbon dioxide per year needed in the absence of any extreme poverty eradication. Lower inequality, higher energy efficiency, and decarbonization of energy can significantly ease this trade-off: assuming the best historical performance in all countries, the additional emissions for poverty eradication are reduced by 90 percent. Therefore, the need to eradicate extreme poverty cannot be used as a justification for reducing the world's climate ambitions. When trade-offs exist, the eradication of extreme poverty can be prioritized with negligible emissions implications. The estimated emissions of eradicating poverty are 15.3 percent of 2019 emissions with the lower-middle-income poverty line at $3.65 per day and or 45.7 percent of 2019 emissions with the $6.85 upper-middle-income poverty line. The challenge to align the world's development and climate objectives is not in reconciling extreme poverty alleviation with climate objectives but in providing middle-income standards of living in a sustainable manner. .

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The Climate Implications of Ending Global Poverty

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Eradicating extreme poverty and stopping climate change are two urgent global challenges, and they can only be tackled together. Eradicating extreme poverty in a sustainable manner requires limiting the future socioeconomic and environmental impacts of climate change; and there is broad consensus that, to be feasible and sustained, the emissions reductions needed to stop climate change have to be achieved through a just transition, which in particular protects the poorest and most vulnerable.[1,2]

The Sustainable Development Goals (SDGs), aspiring to a 'better and more sustainable future for all', attest to the combined importance of these issues. The first of the SDGs calls to 'end poverty in all its forms everywhere'. Eradicating poverty is also atop the agenda of the World Bank, which aims to decrease the share of people living in extreme poverty – with less than \$2.15 a day at 2017 PPP – to 3% or less by 2030.[3] SDG 13 focuses on 'urgent action to combat climate change and its impacts'.[4] To this end, the Paris Agreement was adopted in 2015 by 196 countries with the goal to limit global warming to "*well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels*." This would require reaching global net-zero emissions levels by or close to mid-century, with emission reductions going well beyond the reductions that have been achieved so far.[5,6]

Eradicating extreme poverty requires raising the consumption levels of the global poor to at least \$2.15 a day. However, rising income and consumption levels have historically been the main drivers of increasing CO2e emissions.[7] This raises the question whether, and under which conditions, containing climate change and eradicating poverty are compatible goals.

Existing research has approached this question by calculating the carbon footprint associated with the consumption of individuals at different income levels using consumption and expenditure surveys.[8–10] These studies simulate shifting up the consumption value of the world's extreme poor to the poverty line and estimate the emissions associated with this hypothetical consumption shift. Studies using this approach have generally found that eradicating poverty leads to modest increases in global emissions, with estimates ranging from less than 1% to about 3%.

Here we approach this question with a different, more realistic, framing. Poverty reduction occurs by a combination of economic growth and distribution of this growth across households, with 90% of historical poverty alleviation driven by economic growth.[11–14] We estimate the carbon emissions implications of various growth scenarios (for aggregate growth and the distribution of this growth among the population) under which poverty would be eradicated. With this framing, eradicating poverty requires not only to increase the consumption of poor people but also, under realistic assumptions for the distribution of growth based on historical patterns, to increase the consumption of non-poor people. Therefore, eradicating poverty is expected to lead to higher emissions with this framing than in previous studies if the energy and carbon contents of economic growth follow historical patterns.

To achieve the world's poverty and climate objectives, the future will need to differ markedly from the past. In particular, we analyze how changes in income inequality and in the energy and carbon intensity of economic growth can contribute to reconciling poverty and climate goals. Previous studies have documented stark inequalities in emissions between poorer and richer individuals and households, drawing attention to high emitters in all countries, which contrast with the minimal emissions contributions of the world's poorest.[15–17] A separate body of research examines whether reducing income inequality increases the emissions intensity of GDP.[10,18–23] Here we show that lower inequality means that less growth is needed to eliminate extreme poverty, which in turn reduces the emissions of poverty alleviation significantly. On the flipside, rising inequality can escalate the carbon cost of poverty alleviation and exacerbate the trade-off between climate goals and eradicating even extreme poverty.

With increasingly stringent climate policies and green technologies – like renewable energy and electric transportation – becoming cheaper than fossil fuel equivalent, future economic growth is expected to be more energy efficient and less carbon intensive. We further show the extent to which these changes can reduce the emissions of poverty eradication[24] and estimate the rates of decarbonization that would be required in non-poor countries to offset these emissions.

Results

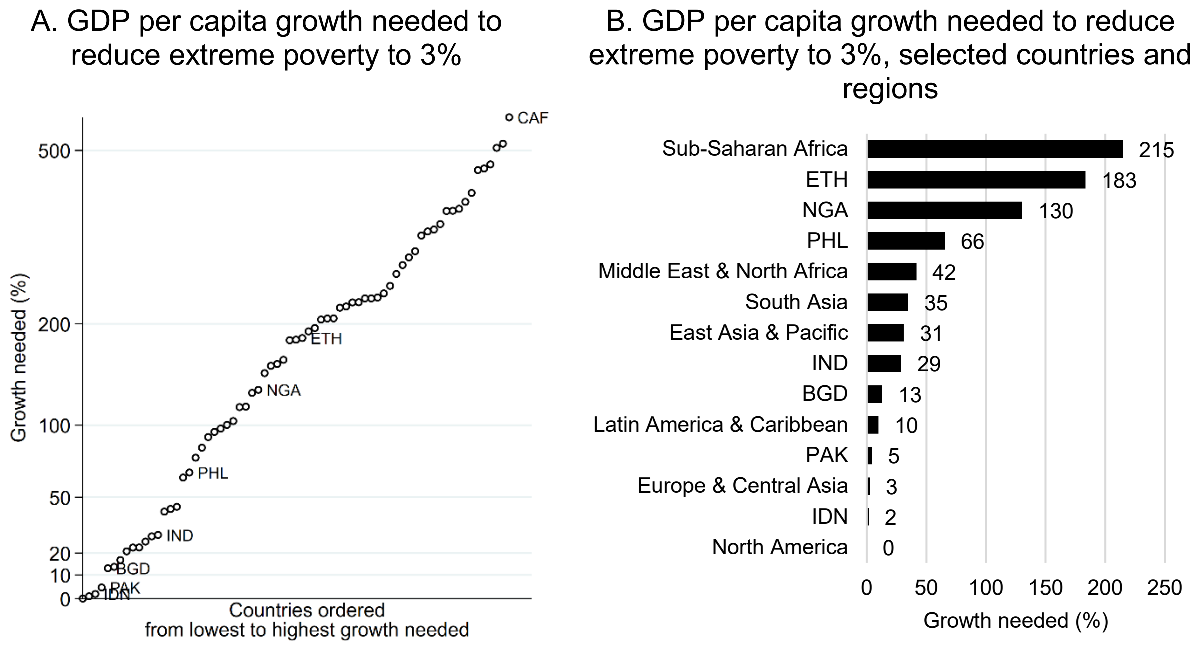
How much economic growth is needed to end extreme poverty? We estimate the historical relationship between growth in GDP per capita and growth in consumption per capita in a random slope regression model, taking into account trends across and within countries. We use data for 168 countries from the World Bank's 2022 Poverty and Shared Prosperity Report[25], converting income distributions to consumption distributions where needed. We also winsorize daily per capita consumption at a value of $0.50 as lower values likely reflect measurement error. We find that, on average, when GDP per capita grows by 1%, consumption per capita grows by 0.7%, with variation between countries (the remainder of growth in GDP per capita is likely being allocated to savings which would imply that the savings rate converges to around 30% in the long term). Using the international extreme poverty line at $2.15 in 2017 USD PPP, we focus, in our baseline model, on the poverty target of reducing the share of people living in extreme poverty to 3% or less, the World Bank's global poverty target and the UN's interpretation of ending extreme poverty in the SDGs.[3] We estimate the growth necessary to reach this target in each country, assuming to begin with an unchanged distribution of consumption within countries and modeling population growth until 2050 according to UN forecasts.[26]

The per capita GDP growth needed to reduce extreme poverty to 3% ranges from zero to nearly 600% -- a sixfold expansion of the economy (Figure 1, panel A). Non-poor countries require zero growth as the poverty target is already reached. North America is the only region in which all countries have achieved this poverty target, while countries in Sub-Saharan Africa need to grow on average by 215% to reach it (Figure 1, Panel B). Targeting higher poverty lines ($3.65, $6.85 – poverty lines typically of lower and upper-middle income countries respectively[27]) requires more growth in more countries than targeting extreme poverty, as more countries are considered poor against higher poverty lines (zero to 1117% at $3.65; zero to 2251% at $6.85; Extended Figure 5). A minimum consumption level of $15 per day in all countries would need per capita GDP growth ranging between zero (in 28 countries) and 5140% (Extended Figure 5). We show the implications of targeting poverty rates other than 3% (5%, 4%, 2%, 1%, 0%; Extended Figure 13).

With historical energy-intensity patterns, how much energy is required for economic growth? To link GDP growth with greenhouse gas (GHG) emissions, we first relate GDP per capita to energy consumption per capita and then relate energy consumption per capita to greenhouse gas emissions. For this, we combine GDP data from the World Development Indicators (WDI) with data from the Energy Information Administration (EIA) on primary energy consumption and with data on GHG emissions from Climatewatch/CAIT, all for 2010 to 2019 (the latest year the data are available).

We again use a random slope regression to model the relationship between GDP and energy consumption, which also allows for efficiency gains over time. The random slope model exploits both variation between countries and variation within countries, and in this case allows for countries to convert GDP to energy needs at different rates and improve (or deteriorate) in energy efficiency at different rates. We cap the distribution of country-level coefficients at the 10th and 90th percentiles as the extreme values likely reflect measurement error or historical patterns that are unlikely to continue in the future.

Figure 1



Note: Panel A includes all countries with an extreme poverty rate greater than 3% in 2022. BGD=Bangladesh; CAF=Central African Republic; ETH=Ethiopia; IDN=Indonesia; IND=India; NGA=Nigeria; PAK=Pakistan; PHL=Philippines (ISO 3166-1 alpha-3 country codes).

We find two patterns. First, there is a time trend, whereby economies have become more efficient across the period we study, at a rate of 1% per year, independent of GDP levels. Second, after accounting for the time trend, 1% growth in GDP per capita leads, on average, to a 1% increase in energy consumption, though this relationship is different for each country. Overall, we do not find that economies become more energy efficient with GDP growth, but we find they do with time.

With historical carbon-intensity patterns, how do emissions increase with energy consumption? We use the same setup to model the relationship between energy consumption and GHG emissions. We find that for a 1% increase in energy consumption, GHG emissions grow by 0.7%, with no significant time trend. This means that countries' emissions grow more slowly than their energy needs, possibly because countries with higher energy consumption are more electrified, which in turn is associated with lower emissions. We also consider non-energy GHG emissions; however, we find no statistically significant association between GDP growth and non-energy emissions in the data, so we exclude non-energy emissions from the analysis (Extended Figure 11).

With historical energy- and carbon-intensity patterns, how much additional emissions are needed to eradicate poverty? We combine the estimates of the growth-poverty and the growth-emissions relationships to estimate the carbon emissions needed for poverty alleviation. To do so, we compare a counterfactual *no-poverty-reduction* scenario with a set of *poverty-eradication* scenarios.

- The counterfactual *no-poverty-reduction* scenario assumes consumption distributions remain unchanged and there is no growth in per capita GDP in poor countries (where poverty eradication has not been achieved) and therefore no poverty reduction. Population grows according to UN projections and the estimated historical patterns and rates of improvement in energy consumption and carbon intensity hold going forward until 2050.

- For the reference *poverty-eradication* scenario, all parameters remain the same as in the *no-poverty reduction* scenario, except for per capita GDP growth which is calibrated to achieve full poverty eradication by 2050. In practice, we extrapolate current economic growth forecasts into the future in each country until the poverty reduction target is reached. For instance, in India, the 3% target would be met in 2027, based on current growth trends. Once the target is met in a country, we only count the GHG emissions associated with countries maintaining GDP per capita levels to keep people out of poverty. For countries that are not expected to grow enough to reach the poverty target by 2050, such as Nigeria, we instead model an annualized per capita economic growth rate that meets the poverty target in 2050. We show the implications of using other target years than 2050 in Extended Figure 13.

The emissions needed for poverty eradication are defined as the difference in emissions between the *poverty-eradication* scenario and the counterfactual *no-poverty-reduction scenario,* that is, the emissions from all per capita GDP growth occurring in poor countries until the poverty target is reached. For countries that are expected to reach the extreme poverty target by 2050, based on current growth trends, like India, the most likely future scenario will see more economic growth (and consequently emissions) than both the counterfactual no-poverty-eradication scenario and the poverty eradication scenario. For countries that are not expected to reach the target by 2050, like Nigeria, the most likely future scenario will see less growth (and emissions) than we model in the poverty-eradication scenario but more than in the no-poverty-reduction scenario (Extended Figure 12).

The important difference of this approach relative to previous studies is that we count the additional emissions from higher consumption of all people in each country (including non-poor people), not only the additional emissions from the people moving out of poverty. In India, for instance, around 6% of the population would need to exit extreme poverty for the target to be reached, but we count the additional emissions *from the entire population* caused by the economic growth needed for eradicating poverty.

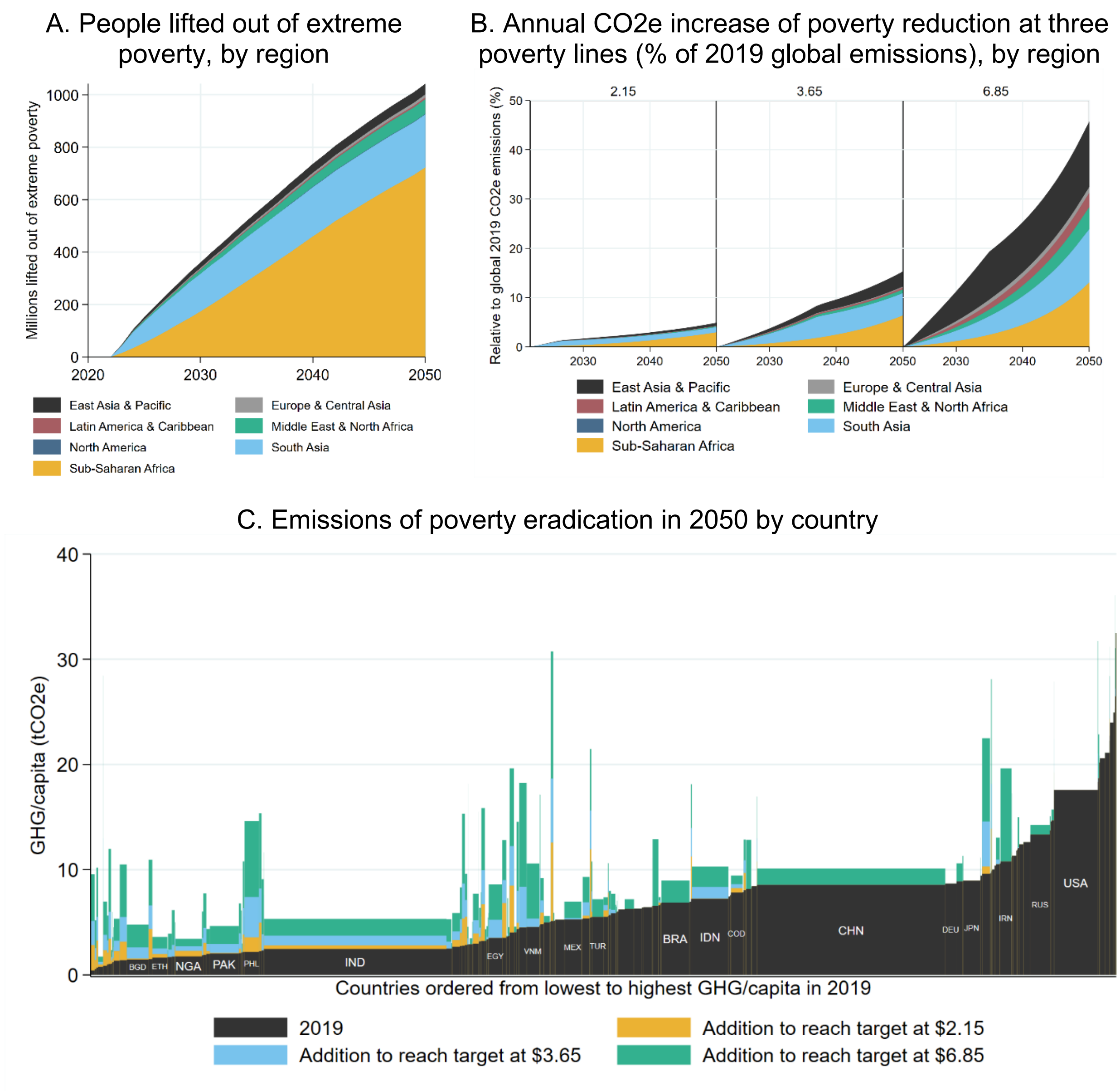
Figure 2, panel A shows the number of people lifted out of extreme poverty between 2023 and 2050 relative to the *no-poverty-reduction* scenario, amounting to just over 1 billion in 2050. Of the 1 billion, 69% are in Sub-Saharan Africa, 19% in South Asia, and 5% in the Middle East and North Africa. Panel B shows the emissions associated with poverty eradication at different poverty lines.

We find the emissions associated with extreme poverty alleviation to be modest. Annual emissions are estimated to be 2.37 gigatons of CO2e (or 4.9% of 2019 global emissions) higher in 2050 when the extreme poverty target is reached, relative to the no poverty reduction scenario. Figure 3 shows that emissions increases are small in the initial years (0.3% in 2023) and increase through time as more and more people are lifted and kept out of poverty (1.7% in 2030, 2.9% in 2040). Of the additional emissions in 2050, 60% accrues in Sub-Saharan Africa, followed by 21% in South Asia, and 12% in East Asia & Pacific. At the country-level, 20% of additional emissions in 2050 accrues in India, followed by 6.3% in the Philippines, and 6% in Angola.

Achieving more ambitious poverty targets has more significant emissions consequences. Using the lower-middle-income poverty line of $3.65 per day, rather than the extreme poverty line of

$2.15 per day, triples the increase in annual emissions in 2050 to 7.4 gigatons or 15.3% over a scenario with no poverty alleviation, compared to 4.9% with the extreme poverty line. With the upper-middle-income poverty line of $6.85 per day, the annual emissions in 2050 increase by 22.1 gigatons or 45.7% (expressed as a fraction of 2019 emissions levels). At $15 per day, the added annual in 2050 increase further to 56.9 gigatons, more than all global 2019 emissions levels (118%; Extended Figure 13).

Figure 2



Note: In Panel C, the width of each country's bar is scaled to their population in 2019. The yellow areas show the CO2e needed to end extreme poverty in 2050, expressed relative to the country's emissions in 2019. The sum of the blue and yellow areas show the CO2e needed to reach the target at $3.65, and equivalently for $6.85.

The results are relatively modest at the $2.15 line because the emissions of poor countries are small relative to wealthier countries – even if they reach the income level necessary to eliminate poverty (Figure 2, Panel C). In contrast, at the $6.85 line, and even more so with a minimum consumption level of $15 per day, the added GHG for poor countries to reach the poverty target starts to have a notable impact on the global emissions. At the same time more countries, such as China, Brazil, Indonesia, and the Russian Federation, require growth to meet the target at that line and the regional distribution of the additional emissions changes (Extended Figure 5). In the case of $6.85 per day, 29% accrue in East Asia & Pacific, 28% in Sub-Saharan Africa, and 24% in South Asia (Figure 2, panel B), while the countries with the largest shares of added emissions in 2050 are India (18%), China (10%), and the Philippines (6%).

What is the trade-off between ending poverty and limiting global warming? Regardless of future poverty alleviation, containing global warming requires aggressive reductions in global GHG emissions to reach zero net emissions: to reach the most ambitious temperature target of the Paris Agreement, net emissions should reach zero by mid-century. With a 2-degree target, net zero emissions need to be achieved soon thereafter. Even if all new growth in poor countries would (unrealistically) follow historical energy- and carbon-intensity patterns and rates of improvement, eradicating extreme poverty does not affect materially the climate change challenge: instead of reducing emissions by 100%, the world needs to reduce emissions by 104.9%. (As net zero emissions is expected to be achieved with a combination of emission reductions and carbon removals from the atmosphere, this would require more carbon removals or more emission reductions.)

In the *no-poverty-reduction* scenario, reaching net zero emissions in 2050 requires reducing annual global emissions by 2.0 GtCO2e per year, factoring in energy and non-energy emissions as well as population growth, but no growth in GDP per capita in poor countries. How much harder is it to achieve net-zero while also eradicating extreme poverty by 2050? In our reference *poverty-eradication* scenario, annual reduction requirements rise modestly by 4% to 2.08 gigatons.

Another way of measuring the trade-off is to look at the change in energy carbon intensity needed to compensate for the additional emissions of ending extreme poverty. To end extreme poverty without increasing emissions compared to the baseline without poverty reduction at all, non-poor countries would need to decarbonize energy consumption at an average rate of 0.28% per year above and beyond current trends. This represents a small increase in ambition relative to what would be required to reach the 1.5C or 2C warming goals, at 5.9% and 2.4% per year, respectively.

Aiming for more ambitious poverty targets creates a more acute trade-off. At the lower-middle-income poverty line of $3.65 per day, the emissions reductions required to achieve net-zero by 2050 are 2.14 GtCO2e per year. Decarbonization at a rate of 1% in non-poor countries and 2.15% in poor countries above the current trends would offset the additional emissions from poverty alleviation.

With the upper-middle-income poverty line of $6.85 per day, the annual global emissions reductions required to achieve net-zero rise to 2.42 gigatons per year each year between 2023 and 2050. To offset the emissions of poverty eradication, non-poor countries would need to decarbonize at a rate of 9.3% per year. This rate substantially exceeds decarbonization rates consistent with 1.5C or 2C warming trajectories. In comparison, poor countries (relative to the $6.85 per day poverty line) would need to decarbonize at a rate of 2.6% above current trends.

So far, we have explored scenarios based on historical patterns and relationships between growth, poverty, energy consumption and GHG emissions. However, historical patterns will need to change for the world to achieve its climate and poverty goals. How does this affect our results? Here we explore changes in inequality (affecting the link between growth and poverty), energy efficiency (affecting the link between growth and energy consumption) and carbon intensity (affecting the link between energy consumption and GHG emissions).

How does inequality impact the emissions needed for poverty eradication? Changes in inequality matter for the emissions of poverty alleviation since they affect the economic growth needed to eradicate poverty. As countries become more equal, the poorest will move closer to the poverty line, and less growth is needed to alleviate poverty. We explore how reducing inequality affects the emissions associated with achieving the poverty target. The Gini coefficient is the most common measure for inequality, ranging from 0 (equal) to 1 (unequal). A 1% decline in the Gini coefficient, in our model, can be interpreted as the reduction in inequality that would come about if a flat 1% consumption tax was levied, and its revenues evenly redistributed among all individuals (ignoring behavioral effects). We model a scenario in which poor countries experience a decline in the Gini coefficient at the rate of the top 10% historical Gini declines over a 28-year period – a reduction of around 17% until 2050.

There is debate over whether lowering inequality may also directly affect emissions by changing consumption patterns along the income distribution, or by enabling climate policies that reduce emissions, with mixed empirical evidence.[18,19,22,28] We assess the relationship of inequality and energy consumption using the random slope model and find no significant effect of inequality on energy consumption conditional on GDP, and we consequently leave it out of our model.

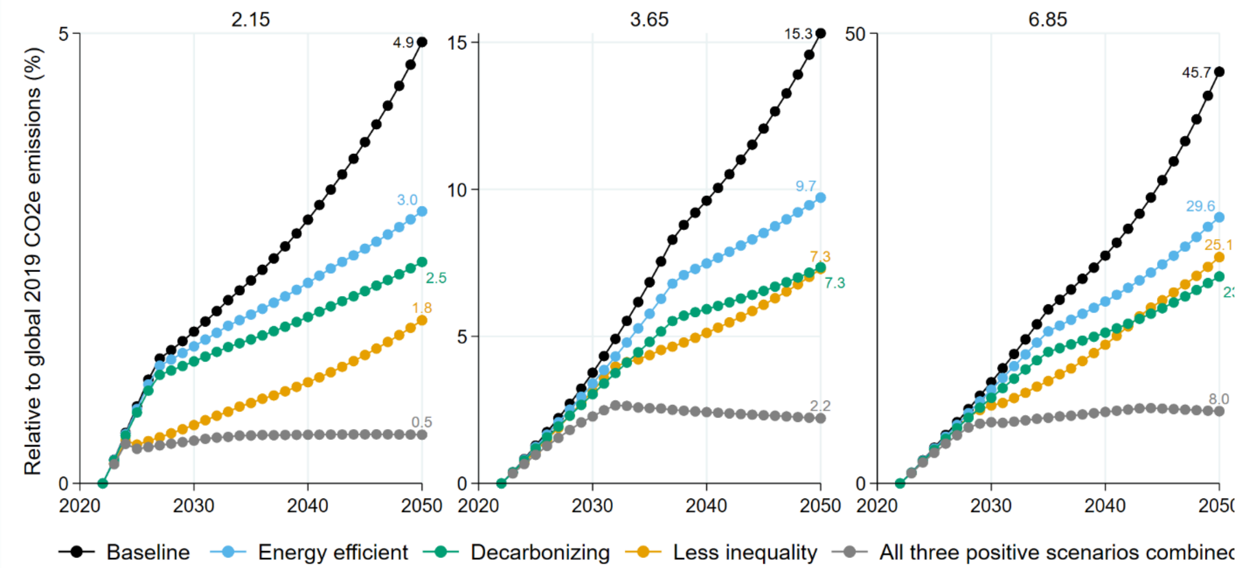
We find that lower inequality significantly reduces the carbon emissions needed for poverty alleviation with historical energy and carbon patterns. In the *reduced-inequality* scenario, the carbon emissions increase associated with eradicating extreme poverty in 2050 is 876 million tons (or 1.8% of 2019 emissions levels) – just over a third of the 4.9% in the baseline scenario with no inequality change (Figure 3).

How do changes in energy- and carbon-intensity impact the emissions needed for poverty eradication? Achieving the world's climate goals will require unprecedented changes in energy- and carbon-intensity and future economic growth cannot be expected to have the same intensities as historical patterns. Even without climate policies, renewable energies have now become cheaper than fossil fuels in most countries, and further progress in energy efficiency (including through electrification of heat and transportation) will make future growth less intensive in energy and carbon.[29]

To explore these effects, we consider first cases in which all poor countries increase energy efficiency and decarbonize energy consumption related to *new* production at the rate of the top 10% historical performers as estimated in the random slope regression model. (For now, the existing production level is assumed to maintain the same energy efficiency and carbon intensity.) This represents the best historical performance and translates to improvements in energy efficiency of new GDP of 2.2% per year and reductions in carbon intensity of energy of 3.2% per year. For reference, reducing energy and carbon intensity to levels consistent with a 2C warming trajectory would require average annual improvement rates of 3.5% and 2.4%, respectively. For levels consistent with a 1.5C warming trajectory, these reductions need to reach 4% and 5.9%, respectively.[30]

Figure 3

CO2e emissions of poverty alleviation at different poverty lines: baseline estimate vs lower inequality, higher energy efficiency, or decarbonization



The best historical performance for increased energy efficiency reduces the emissions of poverty reduction in 2050 to 1.46 gigatons or 3.0%, compared to 4.9% in the reference poverty-eradication scenario. The best historical performance for decarbonization halves the emissions of poverty alleviation in 2050 to 1.19 gigatons or 2.5% (Figure 3).

Combining all three scenarios – lower inequality, and energy efficiency and decarbonization of the new production only – brings the emissions of poverty alleviation down to 261 million tons or 0.54%, a reduction of almost 90% relative to the reference scenario, making the impact of poverty eradication on carbon emissions almost negligible.

For the $3.65 poverty line, lower inequality, improved energy efficiency, and reduced carbon intensity of energy individually limit the emissions increase in 2050 of reaching the target to 7.3%, 9.7%, and 7.3%, respectively; and to 25.1%, 29.6%, and 23.0%, respectively, for the $6.85 poverty line (Figure 3). Combining all three policies further limits the emissions increases: at the $3.65 poverty line from 15.3% to 2.2% relative to a scenario without any poverty alleviation; at the $6.85 poverty line from 45.7% to 8.0%.

Here, we have looked at improvements in energy and carbon efficiency for the added production only. But progress in energy efficiency and decarbonization is expected to also reduce the emissions from existing production (for instance when a factory uses electricity that becomes increasingly decarbonized, or when it delivers its production with electrified vehicles). Applying the same improvements in energy and carbon intensity to both *new and existing* production (rather than just to the new production) would more than offset the emissions of poverty eradication. It means that if poor countries decarbonize their existing production at the rate of the best historical performers, they can eradicate extreme poverty while reducing their emissions, achieving decoupling of poverty reduction and GHG emissions.

We finally consider cases in which all poor countries follow the path not of historical best but historical worst performers. In these scenarios, poor countries experience rising inequality (13% increase in the Gini by 2050), increasing energy intensity of GDP (+2.1% per year), and increasing carbon intensity of energy (+2.5% per year; Extended Table 4). In these cases, emissions even for extreme poverty eradication increase substantially, to 11.3% with rising inequality and to 8.8% and 10.3% with increasing energy and carbon intensity, respectively, compared to 4.9% in the baseline scenario. We explore a wider range of scenarios and their associated emissions in the appendix, based on the different combinations of inequality, energy and carbon intensity, and other key modeling parameters.

Discussion

We study the potential trade-offs between poverty eradication and limiting global warming. Our approach to this issue is to estimate the GHG emissions from the economic growth needed to eradicate extreme poverty under different inequality, energy-intensity, and carbon-intensity assumptions.

The main finding of this study is that, at the global level, the trade-off between eradicating extreme poverty and containing global warming is small, and the need to eradicate extreme poverty cannot be used as a justification for reducing the world's climate ambitions. This result of course does not mean that there are no trade-offs between poverty alleviation and GHG emissions *for specific policies or investments or related to some budgetary constraints*, even though recent work points toward more synergies than trade-offs.[31] When poverty reduction requires increases in GHG emissions, our second conclusion is that the eradication of extreme poverty can be prioritized, since the emissions implications will always remain very limited (at least if the energy- and carbon-intensities are as good as historical standards). Therefore, our results show that the challenge to align the world's development and climate objectives is not in reconciling extreme poverty alleviation with climate objectives *but in providing middle-income standards of living while decarbonizing the world economy*. Our analysis faces important limitations. The modeling framework is deliberately simple to allow transparently comparing the emissions associated with different growth and income distribution scenarios consistent with poverty eradication. It is designed to explore scenarios, not to provide forecasts or predictions of future economic growth or carbon emissions.

Moreover, the model draws on historical data, which by construction constrains the range of modeled pathways to what has been observed in the past and makes the results overly pessimistic by ignoring the recent progress in green technologies and solutions. Indeed, new technologies and circumstances create new possibilities for future pathways that did not exist in the past.[32] For instance, new evidence shows that renewable energy sources, rather than fossil fuels, present the most cost-effective way to meet growing electricity demand in many low- and middle-income countries, suggesting that the carbon content of economic growth will be much lower in the future than historically.[31] Particularly relevant for extreme poverty alleviation is the potential from small-scale solar mini-grid in rural areas.[33] Also, there is growing evidence of the potential from energy efficiency measures to generate energy savings and economic benefits, especially linked to electrification of heat (e.g., with heat pumps) and transportation (from electric bikes to electric buses).[34] When low-energy and low-carbon options become more competitive than alternatives, trade-offs between climate and development objectives disappear, even though higher upfront costs and investment needs can represent a major financial challenge.

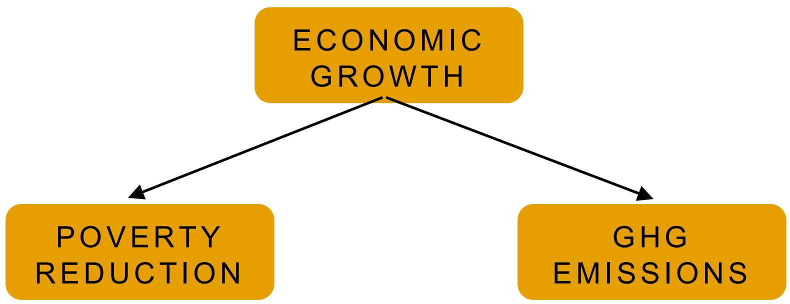
Our estimates rely on monetary poverty measures, based in large part on the consumption value of goods and services. Monetary welfare measures fail to capture all dimensions of well-being or deprivation.[25,35] Importantly, previous research suggested that pathways to ending deprivation and satisfying basic human needs can differ from pathways to eradicating monetary poverty and may be achieved at lower emissions intensity.[36] There are further some methodological challenges concerning the poverty estimates we rely on. Methods and survey designs vary across countries and, since poverty estimates are susceptible to such methodological choices, these differences may affect their comparability[37–39], despite efforts at harmonizing the data across countries.

Our model does not consider certain plausible indirect impacts of the modeling parameters affecting total GHG emissions. For instance, policies to reduce the carbon intensity of growth, such as carbon taxes with a share of revenues used to scale up poverty-reduction programs, can also contribute to reduced inequalities and poverty. And changes in inequality may also lead to additional changes in total emissions which our model fails to capture. Global warming itself is expected to impact poverty levels and may also impact income distributions,[40] while economic growth and reduced poverty may affect population growth.

Methods

Economic growth leads both to poverty reduction[11,41] and greenhouse gas emissions[42,43], as presented in Extended Figure 1. Our approach to estimating the emissions of poverty eradication is divided into two parts according to this simple conceptual framework.

Extended Figure 1: Conceptual framework



1. Economic growth needed to end poverty

1.1 Consumption distributions

Our income and consumption distributions for 2022 come from the World Bank's 2022 Poverty and Shared Prosperity Report[25], a bi-annual flagship report by the World Bank used for tracking extreme poverty and reporting on the first target of the first sustainable development goal. These 2022 distributions reflect the latest harmonized income or expenditure surveys conducted that the World Bank has access to, extrapolated to 2022. Until 2020, the extrapolation done by the World Bank assumes that the entire income and consumption vectors grow according to growth rates in real GDP per capita or Household Final Consumption Expenditure (HFCE) per capita.[44] This means that they keep constant the shape of the distribution and level of inequality observed in the last survey.

Given the unprecedented shock to incomes and consumption in 2020 due to lockdowns, social protection programs, and more, the extrapolation from 2019 to 2020 in the 2022 report relies on another paper which uses actual survey data, simulations from other papers using tax-benefit models, or simulations from high-frequency phone surveys, in that order of preference, to project the distributions forward to 2020.[45] When none of these sources are available, growth rates in GDP per capita are used. From 2020 to 2022, the distributions are once again projected forward using growth rates in GDP per capita or HFCE per capita.

A challenge with the 2022 distributions is that they are a mix of consumption and income aggregates. Richer countries often do not collect detailed consumption data while incomes are hard and less meaningful to measure in poorer countries, where subsistence farming, which rarely is associated with a formal income, is widespread. Income distributions tend to be more unequal than consumption distributions because incomes can be very low (and even negative), while subsistence requires daily consumption to be above a minimum level. At the same time, individuals can have very high incomes in a given year but are unlikely to consume it all, and rather save some for investing and savings. There will likely always be some individuals with very low or negative income each year due to a negative capital shock or for other reasons. Yet this may not imply that their consumption falls below any problematic threshold. This poses a challenge for our study because it is not obvious that income poverty can be ended. For that reason, we convert income distributions to consumption distributions by applying the following formula:

$$\ln(con) = \ ln(inc^{0.93} + 0.68 + 0.26 * \ln(inc_{median})) \qquad (1)$$

This is derived by exploiting 150 surveys spanning 16 countries where for a given year, there exists both an income aggregate and consumption aggregate in the World Bank's Poverty and Inequality Platform. For each of these surveys, the distributions are converted to 100 quantiles of matching income-consumption pairs (i.e. the income and consumption level at a particular quantile for a particular country-year). The functional form in equation (1) is chosen as it reflects a scenario where both the consumption and income distributions follow a 3-parameter log normal distribution while allowing for these distributions to differ based on a country's median income. The fit gives an R^2 of 0.965 and hence highly accurately converts income to consumption distributions. Note that the conversion is not done at the household level, meaning that we do not convert a particular household's income level to a consumption level. Rather, we convert the 2022 distributions to 1,000 quantiles and convert each of the income quantiles to consumption based on the equation above. More details about the income-consumption conversion are available in the appendix.

For about 50 economies home to less than 2% of the world's population, we have no prior income or consumption data at all. These tend to be small high-income countries that do not share microdata as well as very closed countries, such as Cuba and the Democratic People's Republic of Korea. To make the exercise truly global, we impute consumption distributions for these countries by taking the median value of the 1,000 consumption quantiles of their respective World Bank income group and region. For region-income group pairs with fewer than five countries with data, we take the median from the income group for the country with missing data.

Finally, we winsorize the consumption distributions at 50 cents per person per day. Consumption levels below that would reflect a daily caloric intake that likely is impossible to sustain over periods of time, and hence likely reflect measurement error. This winsorization affects 0.4% of the observations. If we do not winsorize consumption, our baseline additional emissions in 2050 relative to 2019 levels for the three poverty lines go from 4.9% to 5.6% ($2.15), from 15.3% to 16.3% ($3.65), and from 45.7% to 47.5% ($6.85). If we winsorize consumption at $1, our results decrease to 3.7%, 13.4%, and 42.5% for the three lines, respectively.

1.2 Poverty lines

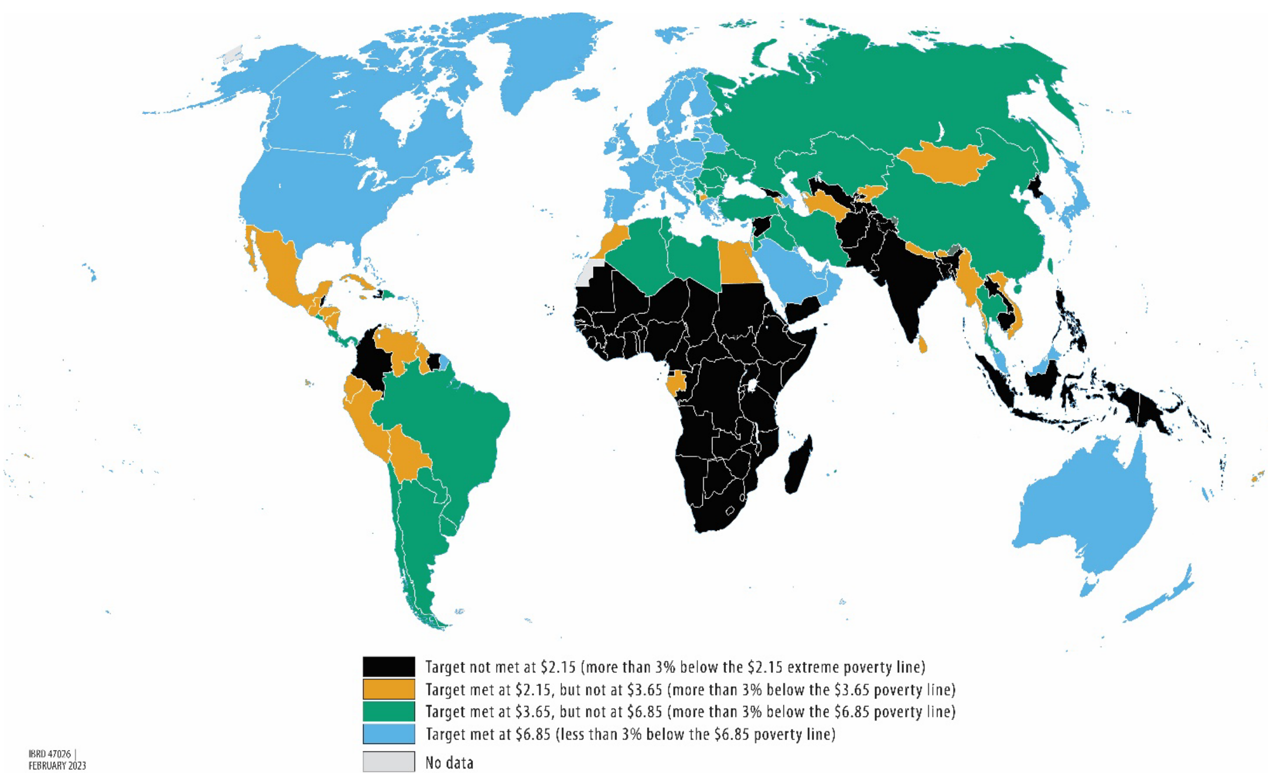
We are primarily interested in the greenhouse gases necessary to end extreme poverty, currently measured as falling short of a daily consumption of $2.15 in 2017 purchasing power parity adjusted dollars.[27] This is the international poverty line used for the first target of the Sustainable Development Goals and the poverty line used for the World Bank's mission goal. It reflects the typical national poverty line of low-income countries. These low-income countries tend to define their national poverty lines as the expenditure necessary to consume about 2,200 calories per day and a small non-food allotment.

The $2.15 line is very frugal and individuals with a daily consumption above this threshold may still live in what would ordinarily be considered poverty. To measure the greenhouse gases needed to end poverty at higher thresholds, we also look at the poverty lines typical of lower-middle income countries ($3.65) and of upper-middle income countries ($6.85).[27]

We could use national poverty lines directly, meaning that each country would have its own threshold. However, since national poverty lines often are explicitly or effectively relative in the sense that they get updated every now and then[46,47], there is no reason to believe that poverty according to national standards will ever be eliminated. Even the wealthiest countries today have poverty according to their national definitions. In the European Union, for example, people are considered to be at risk of poverty if they have a disposable income below 60% of the national median disposable income. Consequently, as European economies grow and median incomes increase, the threshold designating risk of poverty grows in tandem. For that reason, we restrict our analysis to global poverty lines.

For the three poverty lines we will use, we estimate the growth needed to reach a poverty rate of at most 3% -- the current global target at the international poverty of $2.15. This target acknowledges that getting to 0% is very likely not feasible due to possible measurement error in the very bottom of distributions. Extended Figure 2 shows the countries which have already met the 3% target at the three main poverty lines used in the paper.

Extended Figure 2. Categorization by whether countries have met the 3% poverty target



1.3 Consumption growth necessary to end poverty

With constant distribution. Calculating the consumption growth necessary to end poverty in each country is straightforward in the case where growth accrues to all equally, i.e. is distribution-neutral. First, we identify the consumption level of the third percentile. Take the case of Benin where the third percentile reflects a consumption per day of $1.33. For the country to reach the poverty target for the international poverty line in a manner where the consumption of all individuals grows at an equal rate, the third percentile needs to just pass the poverty threshold. This means that the consumption value of individuals at the third percentile needs to grow by $\frac{\$2.15-\$1.33}{\$1.33} = 62\%$. Since we assume growth is distribution-neutral, the entire consumption distribution of Benin would need to grow by 62% to reach the poverty target. By the same logic, everyone's consumption needs to grow by 174% for the country to reach the target at the $3.65 poverty line. More generally, to reach the poverty rate target of P^* (which unless otherwise specified is 3% in our analysis) at the poverty line z, then consumption per capita ($growthconpc$) in country c needs to grow by

$$growthconpc_c^* = \frac{z}{F_c^{-1}(P^*)} - 1, \qquad (2)$$

where $F_c^{-1}(P^*)$ is the consumption level of percentile at P^*.

With changing distribution. The calculation is more complicated in the inequality-sensitive scenarios. The main reason for this is that there are many different inequality metrics and infinitely many ways consumption growth can be allocated for a given change in inequality. We use the Gini coefficient as the inequality metric due to its popularity. We implement changes in inequality that correspond to taxing consumption by x% and distributing the proceedings equally to everyone. It turns out that such a tax and transfer scheme precisely reduces the Gini coefficient by x%.[48,49] This particular change in inequality has been shown to occur frequently on historical data.[50] Concretely it means that if the Gini reduces by x%, then each individual's consumption will be given by:

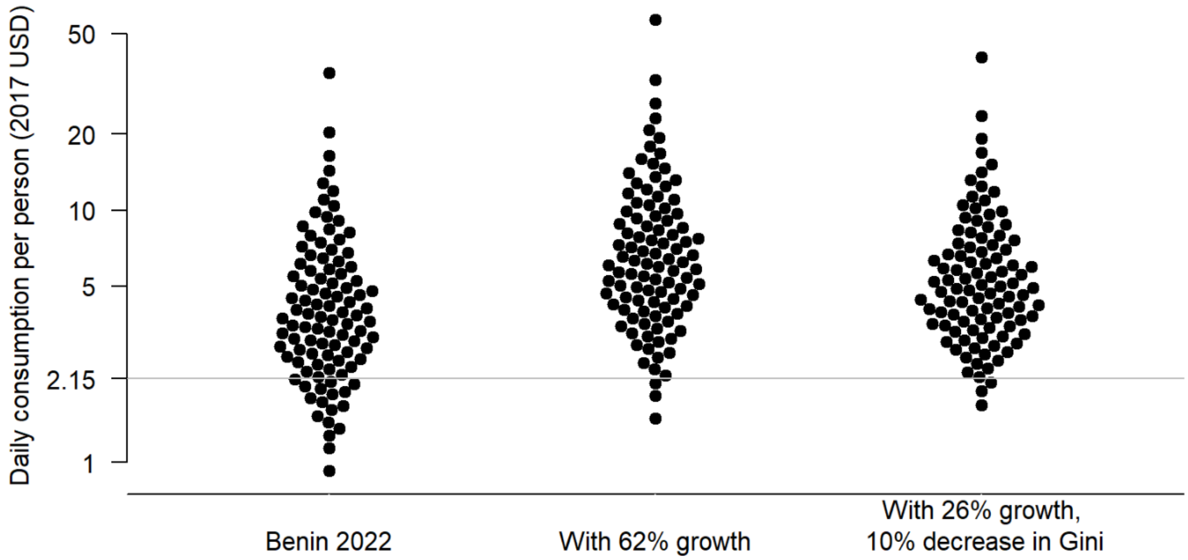
$$con_{new} = con_{old}(1-x) + x * \mu_{con} \qquad (3)$$

where con_{old} is the consumption before the inequality change, con_{new} is the consumption after the inequality change, and μ_{con} is mean consumption per capita. From this equation it is also clear that the Gini reduction at most lowers consumption by x%, so if average growth is larger than x%, then no one will lose consumption as a result of this inequality reduction.

Given that inequality reductions will increase the consumption of the bottom more than average, the 3rd percentile will now move closer (or above) the poverty line, so $F_c^{-1}(P^*)$ will increase, and the growth needed for the 3rd percentile to reach the poverty line will be lower. In Benin, the mean consumption is $5.04, so if the Gini is reduced by 10%, the 3rd percentile obtains a consumption level of $1.70, and the growth needed to reach the target drops from 62% to 26%. All of this is illustrated in Extended Figure 3 below.

Our baseline scenario uses the distribution-neutral case. Though consumption inequality surely will change in the coming decades, historical evidence shows that around 90% of changes in poverty are driven by shifts in mean consumption rather than changes in the distribution of consumption.[13] In addition, a recent exercise attempting to predict changes in the Gini using more than 1,000 variables from the World Development Indicators, World Economic Outlook, and the Google Earth Engine, found that no variable was particularly helpful in predicting changes in inequality.[14] Hence, even if we wanted to try to account for the remaining 10% of historical changes to poverty, it is not obvious how to do so.

Extended Figure 3: Illustration of consumption growth necessary to reach poverty target



Note: The left part shows the distribution of consumption in Benin boiled down to 100 percentiles. The middle and right part show examples of growth and the distribution growth that can make Benin reach the 3% target.

1.4 GDP/capita growth necessary to end poverty

Once we know the consumption growth necessary to end poverty, either in the distribution-neutral case or inequality-reducing case, the next step is to convert these consumption growth rates into growth rates in GDP per capita. One might think that for consumption per capita to grow 1%, GDP per capita needs to grow 1%, but prior evidence has shown a discrepancy between the two.[51–53] There are several possible reasons for this, including that part of growth in GDP is saved rather than being allocated to consumption and that GDP growth may be overestimated in some countries.[54] The discrepancy could also be due to unit nonresponse in surveys or differences in the exact items captured in consumption surveys and national accounts.

To account for this non-one-to-one relationship while acknowledging that the rate at which GDP growth passes through to consumption may differ by country, we fit a random slope model, a variant of what is also known as a multilevel model, a hierarchical linear model, or a mixed model.[55] A random slope model is convenient because it exploits both within and between country information, and because it allows us to generate predictions even for countries without any historical data. Concretely, we fit a model of the following form:

$$\ln\left(conpc_{y,c}\right) = \left(\beta_o + u_{o,c}\right) + \left(\beta_1 + u_{1,c}\right)\ln\left(gdppc_{y,c}\right) + \varepsilon_{y,c} \tag{4}$$

Here the β's are fixed effects constant across countries, while the u's are country-varying random effects centered around zero. We run this regression on the latest time-series of comparable consumption data for each country in the Poverty and Inequality Platform, and match the consumption data with data on GDP per capita from the World Development Indicators supplemented with data from the World Economic Outlook and Madison database where needed. Extended Table 1 shows the regression output.

Extended Table 1: Relationship between per capita consumption and per capita GDP

	Fixed effect (β)	Standard deviation of random effect (u)
Log GDP per capita	0.701***	0.291***
	(0.038)	(0.033)
Constant	-4.170***	2.730***
	(0.345)	(0.320)

Note: *=0.1, **=0.05, ***=0.01. A covariance between the two random effects is estimated as well. Number of countries = 116. Number of observations = 470.
Source: Poverty and Inequality Platform, World Bank, and World Development Indicators, World Economic Outlook, and the Maddison Project Database.

β_1 and $u_{1,c}$ are the parameters of interest. β_1 shows the average rate across countries at which 1% growth in GDP passes through to growth in consumption per capita. β_1 is estimated to be 0.70 with a standard error of 0.038. $u_{1,c}$ is a country-specific add-on reflecting that the passthrough rate differs by country. The standard deviation of $u_{1,c}$ is estimated to be 0.291 (with a standard error of 0.033). Extended Figure 4 shows two countries with a high and low estimated $u_{1,c}$ and the full distribution of the estimated $\beta_1 + u_{1,c}$. The countries with the largest and smallest $u_{1,c}$ likely reflect historical patterns that are unlikely to replicate. For that reason, we cap $u_{1,c}$ at the 10th and 90th percentile (0.44 and 0.98).

We can now back out the GDP/capita growth needed to get to the consumption/capita growth required for ending poverty. Benin, for example, is estimated to have a passthrough rate of 0.68. This means that for the 62% consumption per capita growth (calculated earlier) necessary to occur, GDP per capita needs to grow by 91% (91%*0.68=62%). More generally, the GDP per capita necessary to end poverty is given by

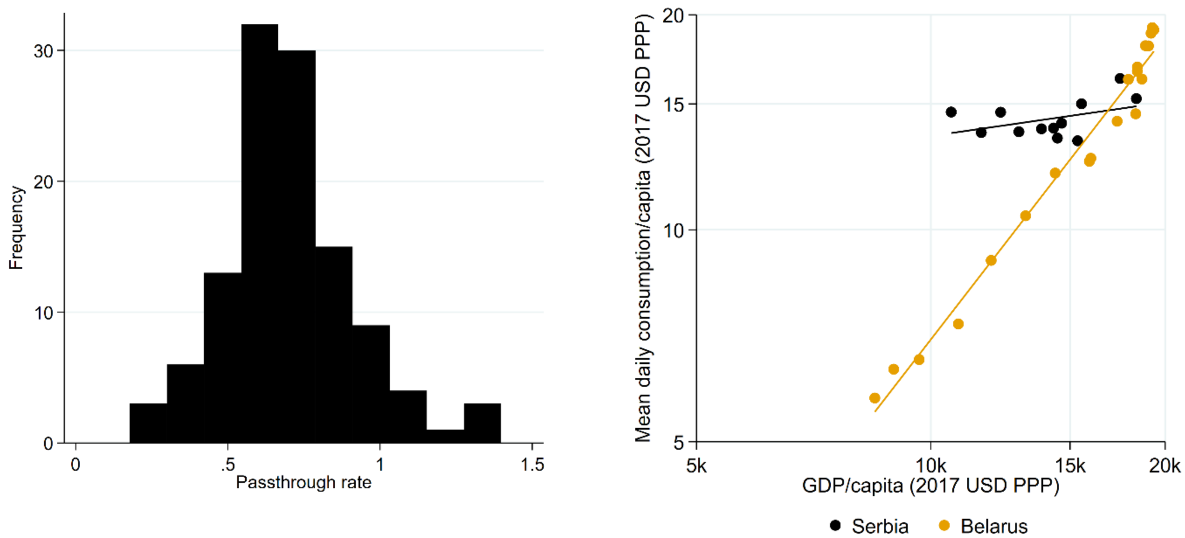
$$gdppc_c^* = gdppc_{2022,c} * \left[1 + growthconpc_c^* / \left(\hat{\beta}_1 + \hat{u}_{1,c}\right)\right] \tag{5}$$

Extended Figure 5 shows the GDP per capita growth needed to reach the 3% target at the \$3.65, \$6.85, and \$15 lines for the countries that did not meet the target in 2022. The similar plot for the \$2.15 line is in the main text.

One could rightfully question whether growth in GDP per capita is the only factor relevant for poverty reduction. Certainly other factors matter as well, such as changes to the unemployment rate, structural transformation, commodity prices, and more. Yet of 1,000 variables used to predict growth in mean consumption, GDP per capita (together with related national accounts concepts, such as HFCE and Gross National Income per capita) are by far the most predictive variables of consumption growth.[14] In fact, conditional on knowing growth in real GDP/capita no other variable is particularly informative about growth in consumption.

Extended Figure 4: Transmission from GDP growth to consumption growth

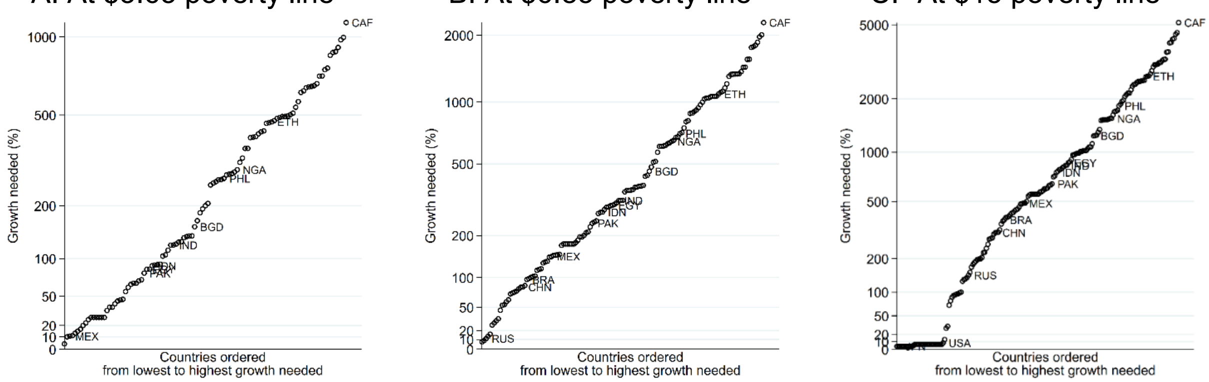
A. Country-specific passthrough rates B. Example of high and low passthrough rate



Note: Panel A shows the distribution of the estimated $\beta_1 + u_{1,c}$ while Panel B shows two examples of countries with a high and low $u_{1,c}$.
Source: Poverty and Inequality Platform, World Bank, and World Development Indicators, World Economic Outlook, and the Maddison Project Database.

Extended Figure 5: Growth needed to reach 3% poverty target.

A. At \$3.65 poverty line B. At \$6.85 poverty line C. At \$15 poverty line



For the next part of the analysis, it will matter when the growth needed to end poverty occurs. In our baseline set-up, we use growth forecasts in real GDP per capita from IMF's October 2022 World Economic Outlook to grow the current level of GDP per capita forward. These growth forecasts only continue until 2027, beyond which we assume that the growth rate for 2027 continues onwards to 2050. If countries have not reached $gdppc_c^*$ by 2050, instead of using IMF growth forecasts, we assign countries the annualized growth rate needed to exactly reach $gdppc_c^*$

by 2050. We do so because some countries are not on track to reach the target GDP level any time soon, and modeling many decades ahead would add to the uncertainty around the results. In Extended Figure 13, we will show how the assumption of all countries ending poverty by 2050 matters for our results.

2. Greenhouse gases associated with the growth needed to end poverty

Once the GDP/capita growth necessary to end poverty is estimated for each country, we calculate the greenhouse gases associated with this growth. We consider greenhouse gases from energy and non-energy separately.

2.1 Energy levels

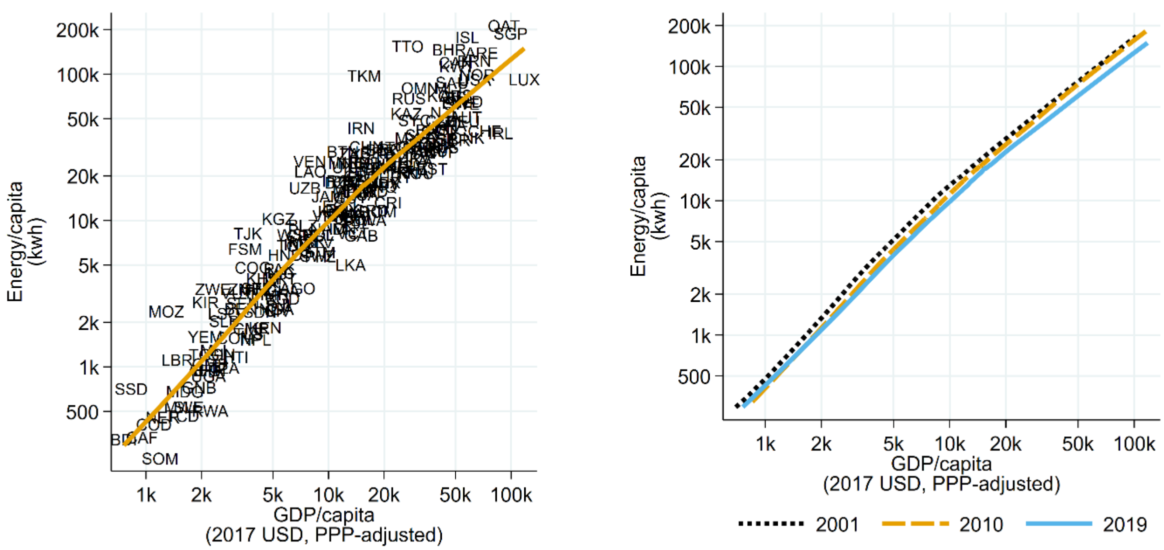
With respect to energy emissions, we take the intermediate step of first modeling energy levels. This has the advantage of allowing us to separately explore the impact of energy intensity of GDP and the impact of carbon intensity of energy. The energy data is drawn from the U.S. Energy Information Administration and covers primary energy consumption.

Extended Figure 6 plots energy per capita as a function of GDP per capita across countries in 2019, the latest year with data at the time of writing, and shows the cross-country fit over the past two decades. Countries with a higher GDP per capita use more energy per capita, and the energy needs for a given level of GDP has decreased over the past two decades. To fit a model to these stylized facts, we once again run a random slope model, this time allowing country variation in how GDP per capita is converted to energy needs and in how energy needs change over time by adding a year variable. This allows countries to produce the same GDP with less energy year-by-year, and for this rate of improvement in energy intensity to vary by country.

Extended Figure 6: Transmission from GDP to energy

A. Cross-country relationship, 2019

B. Relationship over time



Source: World Development Indicators, World Economic Outlook, the Maddison Project Database, and the U.S Energy Information Administration.

We run the model with data from 2010 onwards, since older data may contain patterns that are less relevant for the future. Data before 2010 generally reveal slower annual improvements in energy efficiency. If we reversely restrict the data to fewer, more recent years, we lose power to estimate all the random effects. Occasionally, there are clear breaks in the energy data series, which, if ignored, would give unreliable predictions. We identify breaks by calculating the average annual change in energy consumption per capita by country, and flag whenever an annual change is more than four times the average change for a country. Whenever a break is identified, we only use data after the break. Equation (6) shows the regression we run and Extended Table 2 the results of the regression.

$$lnenergypc_{y,c} = (\beta_o + u_{o,c}) + (\beta_1 + u_{1,c})lngdppc_{y,c} + (\beta_2 + u_{2,c})year + \varepsilon_{y,c} \quad (6)$$

Extended Table 2: Relationship between energy per capita and GDP per capita

	Fixed effect (β)	Standard deviation of random effect (u)
Log GDP per capita	0.998***	0.332***
	(0.038)	(0.043)
Year	-0.009***	0.025***
	(0.002)	(0.002)
Constant	18.279***	49.851***
	(3.964)	(4.486)

Note: *=0.1, **=0.05, ***=0.01. Covariances between the random effects are estimated as well. Number of countries = 218. Number of observations = 1845.
Source: World Development Indicators, World Economic Outlook, the Maddison Project Database, and the U.S Energy Information Administration.

On average, a 1% growth in GDP leads to a 1% growth in energy, but this effect varies greatly across countries, with the standard deviation being 0.33%. Every year, countries on average get 0.9% more efficient at producing the same level of GDP, but again there is large country variation, with the standard deviation of the random effect being 2.5%. Extended Figure 7 shows the histogram of the total effects of GDP and time on energy consumption across countries.

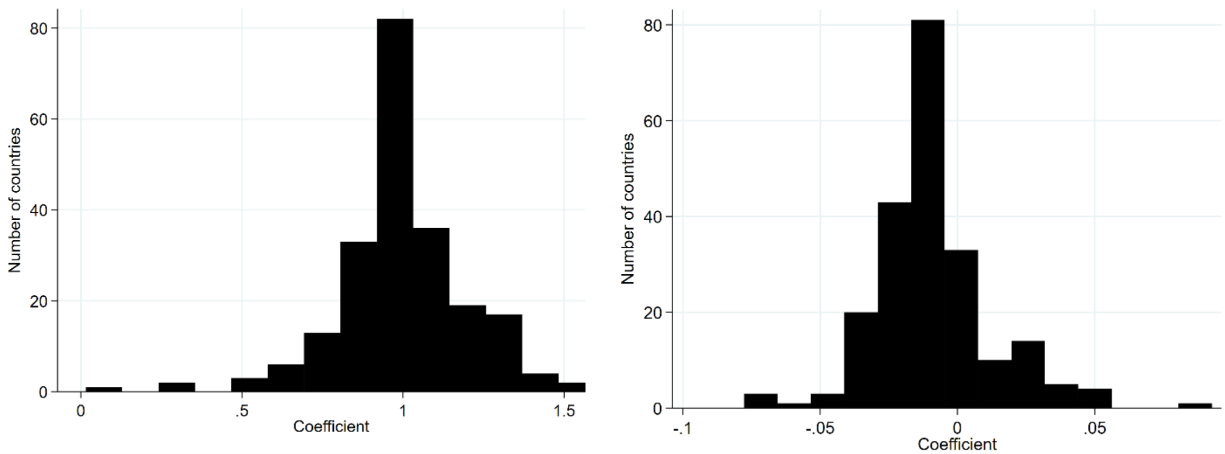
As was the case for the prediction of consumption levels, we once again trim the country-level distributions at the 10th and 90th percentiles, which is 0.78% and 1.27% for GDP/capita and -3.2% and 2.1% for annual change. We do so because the most extreme historical patterns are unlikely to continue in the future. In addition, we also identify the most extreme outliers in the relationship between energy/capita and GDP/capita (evaluated as the residual from the linear trend line in 2022) and shift those towards the trendline so the residual does not exceed the 10th and 90th percentile in the distribution of residuals.

Extended Figure 8 shows our predictions from three select countries with and without these adjustments. The solid lines indicate historical data, the dashed line our unadjusted predictions as the countries move to the GDP/capita necessary to end extreme poverty, and the dotted lines our adjusted predictions. India is not impacted by the adjustments. The fact that its trend line is flatter than the cross-country pattern is to be expected given that predictions incorporate gains in energy efficiency over time. The unadjusted Lao PDR and Somalia patterns show that if historical patterns were to continue into the future, the energy per capita levels would be implausibly high and low, respectively. The adjustments limit the most extreme historical patterns.

Extended Figure 7: Cross-country variety in predictions of energy per capita

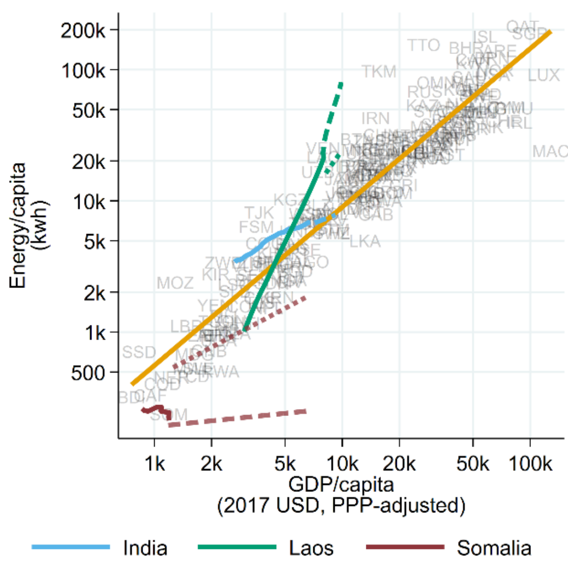
A. Impact of 1% growth in GDP/capita on energy/capita

B. Annual change in energy/capita conditional on GDP/capita



Note: Histogram of estimated random plus fixed effect coefficients. In Panel B, a coefficient of, say, -0.02 implies a 2% annual decline in energy/capita conditional on GDP/capita.
Source: World Development Indicators, World Economic Outlook, the Maddison Project Database, and the U.S Energy Information Administration.

Extended Figure 8: Energy predictions with and without outlier adjustments



Note: The solid orange line indicates the cross-country fit for 2019. The solid remaining lines indicate historical data, the dashed lines predictions unadjusted for outliers, and the dotted lines predictions adjusted for outliers.
Source: World Development Indicators, World Economic Outlook, the Maddison Project Database, and the U.S Energy Information Administration.

Based on all of this, we can predict the target energy per capita level needed to end poverty in 2050 as

$$lnenergypc^{*}_{c,2050} = \left(\hat{\beta}_o + \hat{u}_{o,c}\right) + \left(\hat{\beta}_1 + \hat{u}_{1,c}\right) lngdppc^{*}_{c,2050} + \left(\hat{\beta}_2 + \hat{u}_{2,c}\right) * 2050 \qquad (7)$$

2.3 Energy greenhouse gases

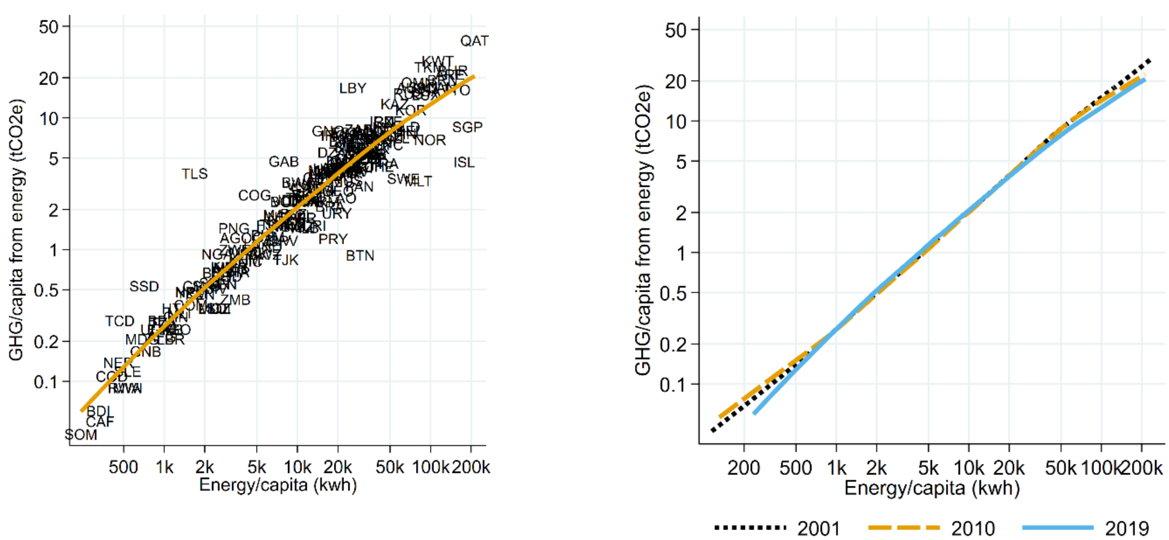
Next, we convert these energy predictions to predictions of greenhouse gases from energy. Extended Figure 9 shows the cross-country relationship and how it has changed over time. There is clear evidence of larger energy needs leading to more energy greenhouse gases, but little evidence of countries improving their ability to produce energy level with less greenhouse gases over time.

Our approach to model these patterns is identical to the one followed above: we once again run a random slope model, this time predicting energy emissions as a function of time and energy levels while allowing for cross country heterogeneity. The regression we run is listed in equation (8), the output is presented in Extended Table 3, and the histogram of coefficients shown in Extended Figure 10.

Extended Figure 9: Transmission from energy to greenhouse gases from energy

A. Cross-country relationship, 2019

B. Relationship over time



Note: The Extended Figures show the relationship between GDP/capita and Energy/capita.
Source: Climatewatchdata/CAIT and the U.S Energy Information Administration.

$$lnghgenergypc_{y,c} = \left(\beta_o + u_{o,c}\right) + \left(\beta_1 + u_{1,c}\right) lnenergypc_{y,c} + \left(\beta_2 + u_{2,c}\right) year + \varepsilon_{y,c} \; (8)$$

Extended Table 3: Relationship between energy and greenhouse gases from energy

	Coefficient (β)	Standard deviation of random effect (u)
Log energy per capita	0.689***	0.303***
	(0.030)	(0.043)
Year	0.002	0.023***
	(0.002)	(0.002)
Constant	-9.966***	46.546***
	(3.677)	(4.653)

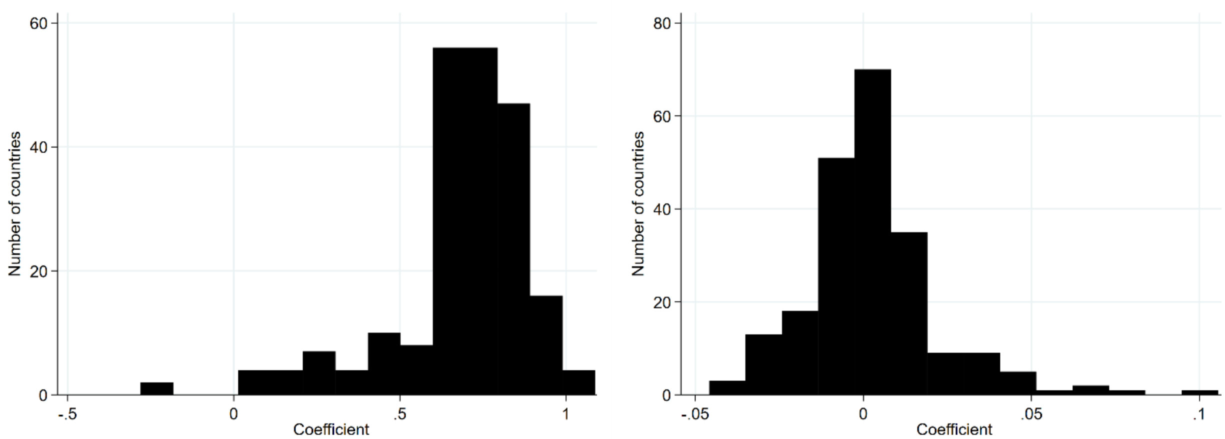
Note: *=0.1, **=0.05, ***=0.01. Covariances between the random effects are estimated as well. Number of countries = 218. Number of observations = 1774.
Source: Climatewatchdata/CAIT and the U.S Energy Information Administration.

The regression output confirms the visual pattern from Extended Figure 9. Higher energy per capita leads to higher greenhouse gases from energy, and there is no evidence of decreased carbon intensity of energy over time. The latter might seem counterintuitive given that the share of renewable energy of total energy has increased over time. Yet rather than being picked up by the time coefficient, this effect is being picked up by the coefficient on energy per capita, which is less than 1% on average. When energy per capita increases by 1%, greenhouse gases per capita from energy on average only increase by 0.69%.

Extended Figure 10: Cross-country variety in predictions of energy greenhouse gases

A. Impact of 1% growth in energy/capita on energy greenhouse gases/capita

B. Annual change in energy greenhouse gases/capita conditional on energy/capita



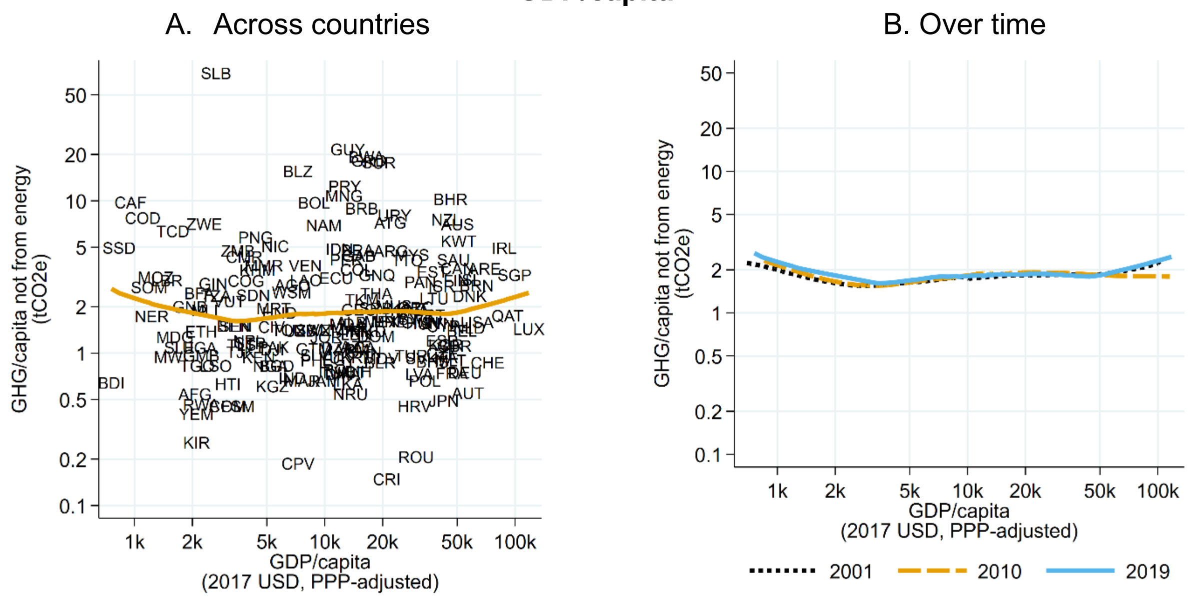
Note: Histogram of estimated random plus fixed effect coefficients. In Panel B, a coefficient of, say, -0.02 implies a 2% annual decline in greenhouse gases from energy/capita conditional on energy/capita.
Source: Climatewatchdata/CAIT and the U.S Energy Information Administration.

We limit the impact of outliers in the same way for the regression of GDP/capita on energy/capita, i.e. at the 10th and 90th percentiles of the distribution of random effects. If we do not winsorize the random effects in any of the regressions and just use the raw random effects, our baseline additional emissions in 2050 relative to 2019 levels for the three poverty lines increase from 4.9% to 6.5% ($2.15), from 15.3% to 18.7% ($3.65), and from 45.7% to 52.9% ($6.85). If we winsorize at the 25th and 75th percentile instead, our results (mostly) decrease to 5.0%, 14.9%, 41.9%.

2.4 Non-energy greenhouse gases

In contrast to greenhouse gases from energy, greenhouse gases from other sources have no systematic relationship with GDP/capita across countries, nor has there been any changes to this over the past 20 years (Extended Figure 11).

Extended Figure 11: Relationship between non-energy greenhouse gases and GDP/capita



Note: Relationship between GDP/capita and greenhouse gases not rom energy/capita.
Source: World Development Indicators, World Economic Outlook, the Maddison Project Database, and Climatewatchdata/CAIT.

Taken at face value, this means that based on historical data, we should not expect non-energy greenhouse gases per capita to increase as a country's economy grows. While there may be exceptions to this pattern, such as countries where non-energy greenhouse gases have increased systematically as a country developed due to deforestation or for other reasons, Extended Figure 11 suggests that for any country where this happened, there is another country where the reverse happened.

When we test this more formally using the same random slope model we have used so far, the impact of growth in GDP per capita on non-energy emissions is not statistically different from zero. For that reason, we exclude non-energy greenhouse gases from the analysis.

3 Greenhouse gases to end poverty

With the modeling above, we can estimate the annual greenhouse gases as currently poor countries approach the GDP/capita necessary to end extreme poverty, which we refer to as the *poverty-eradication* scenario. For 2050, this will equal

$$lnghgenergypc_c^* = \left(\hat{\beta}_o + \hat{u}_{o,c}\right) + \left(\hat{\beta}_1 + \hat{u}_{1,c}\right)lnenergypc_c^* + \left(\hat{\beta}_2 + \hat{u}_{2,c}\right) * 2050 \qquad (9)$$

Some of these greenhouse gases would also be emitted even if poor countries made no progress in eliminating poverty. To quantify the additional greenhouse gases necessary to end extreme poverty, we need a counterfactual scenario. To that end, we calculate annual greenhouse gas emissions for each poor country if they do not grow their GDP per capita beyond their current level: $gdppc_c^o = gdppc_{2022,c}$. We can plug this in equation 7 to obtain $lnenergypc_c^o$, which we then plug into equation 9 to obtain $lnghgenergypc_c^0$ – the greenhouse gases we would expect from the country if it does not grow until 2050 but otherwise follow the exact same patterns as in our poverty eradication scenario. We call this the *no-poverty-reduction* scenario.

Each year, the difference between the poverty-eradication and no-poverty-reduction scenario shows the additional greenhouse gases needed for the country to be on the path to eliminate extreme poverty. In 2050, it shows the additional greenhouse gases needed for the country to eliminate extreme poverty and will be calculated as

$$ghgneeded_{c,2050} = (ghgenergypc_{c,2050}^* - ghgenergypc_{c,2050}^0) * pop_{c,2050} \qquad (10)$$

For the countries that are projected to end extreme poverty before 2050, the poverty-eradication scenario grows economies just until the point where they have reached the poverty target, and after that keeps it constant. Once the poverty target is reached, this means that we estimate the greenhouse gases necessary to maintain a GDP/capita with no poverty.

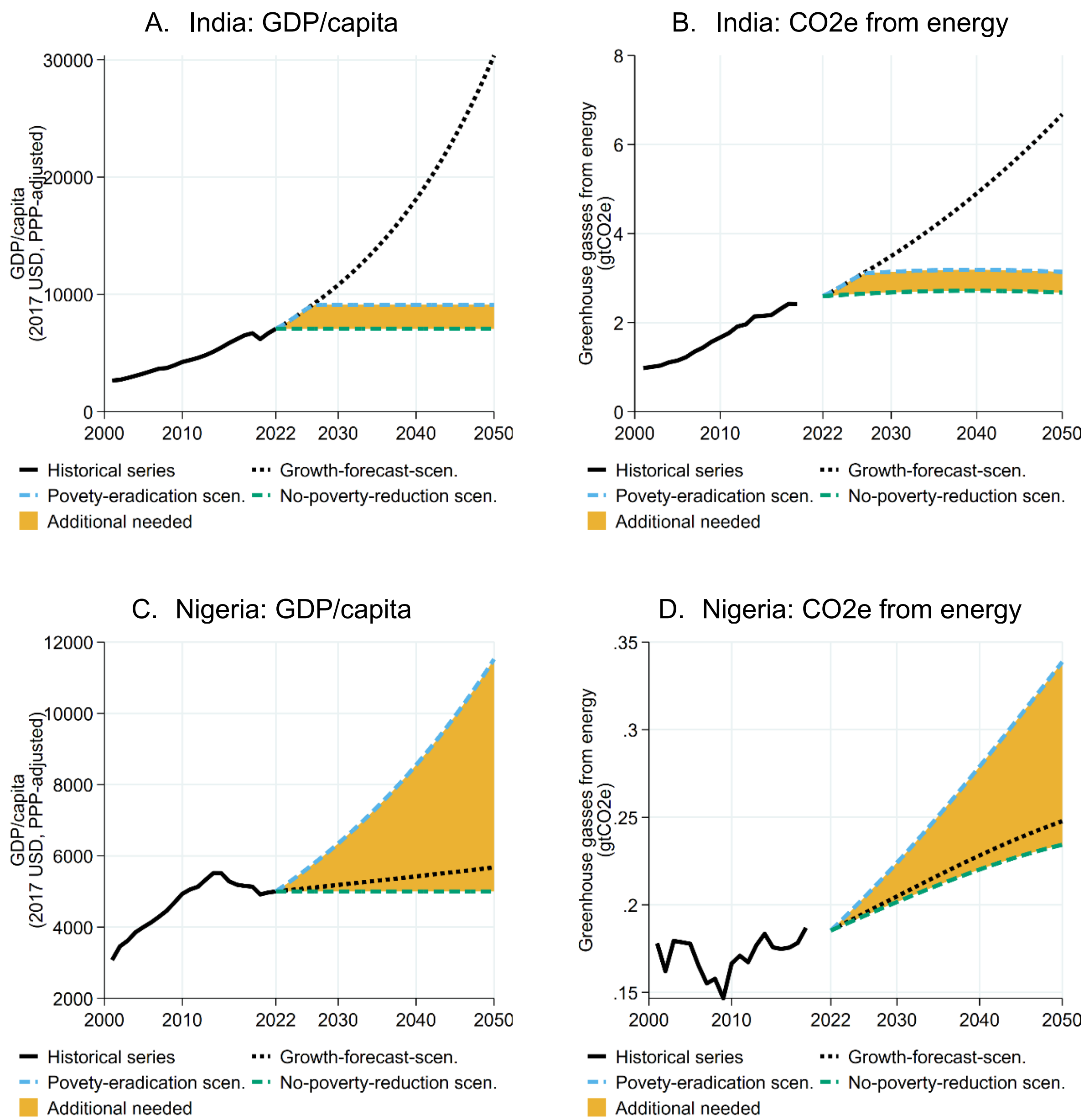
To calculate the total global greenhouse gases needed to end poverty, we simply sum over all countries which had not reached the poverty target in 2022 (C_{poor}):

$$ghgneeded_{world,2050} = \sum_{c \in C_{poor}} ghgneeded_{c,2050} \qquad (11)$$

Extended Figures 12 shows the difference between the poverty-eradication scenario and no-poverty-reduction scenario for India and Nigeria. India is expected to reach the poverty target before 2050 while Nigeria is not, and hence is assigned annualized growth rates such that it just meets the target in 2050. The figures also include a *growth-forecast-scenario*, which shows the GDP and greenhouse gases towards 2050 if the countries grow according to IMF growth expectations, which may be more or less than the growth needed to end poverty.

The greenhouse gases needed would increase notably if a lower target poverty rate is chosen, and vice versa (Extended Figure 13, Panel A). The path of additional greenhouse gases needed would likewise change if we used another year than 2050 as the year in which all poor countries have reached the poverty target. Extended Figure 13, Panel B shows the path if we assume all countries will reach the GDP per capita needed to end poverty in 2023 and then maintain that level onwards to 2050. All the intermediate points on this path are equivalent to the greenhouse gases needed if all countries end poverty by that year. The estimates are increasing over time due to population growth in poor countries – every year there are more and more people to lift out or maintain out of poverty. This population effect dominates the effect from countries every year being more energy efficient and less carbon intensive.

Extended Figure 12: Illustrations of GDP and greenhouse gases needed to end poverty

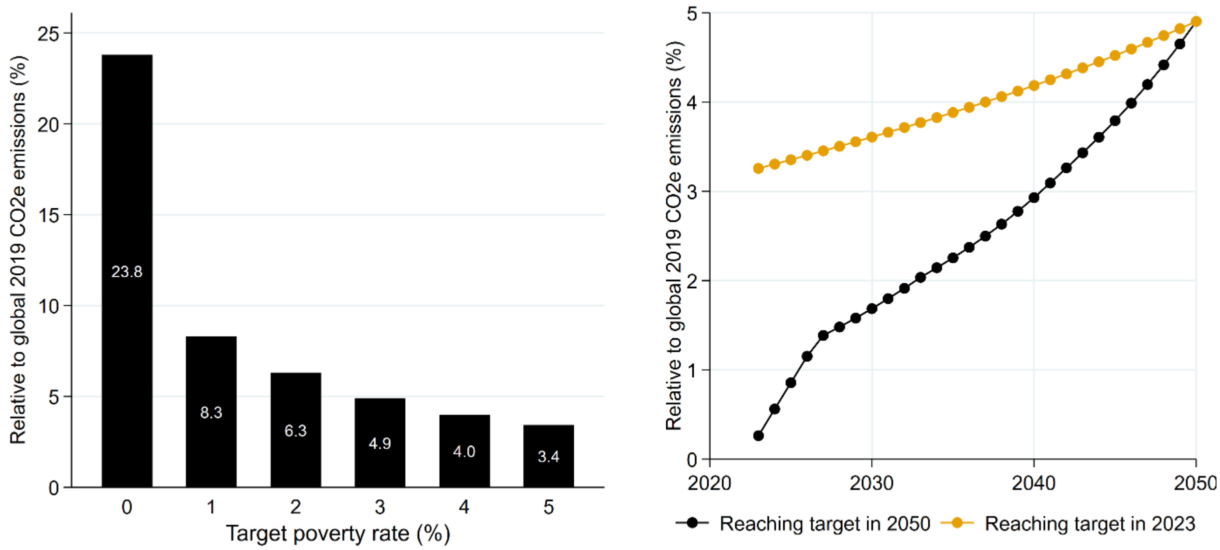


Note: The figures show the difference between the GDP/capita and greenhouse gases needed in the poverty-eradication scenario and no-poverty-reduction scenario, in which poor countries do not grow beyond 2022. The yellow area is the additional GDP/capita or greenhouse gases needed to end poverty.

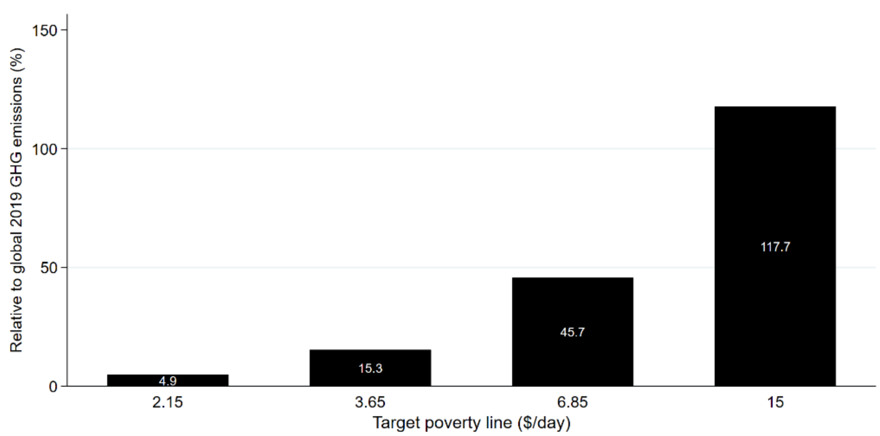
Extended Figure 13. CO2e emissions of poverty eradication at different target poverty rates, lines, and target years

A. By target poverty rate, 2050

B. By target poverty year at $2.15



C. By poverty line, 2050



4 Offsetting the greenhouse gases needed to end poverty

To calculate the decarbonization rate necessary to fully offset the additional greenhouse gases needed to end poverty, we first calculate the sum of additional greenhouse gases needed to end poverty until 2050:

$$ghgneeded_{world,total} = \sum_{y=2022,..,2050} \left(\sum_{c \in C_{poor}} ghgneeded_{c,y} \right) \quad (12)$$

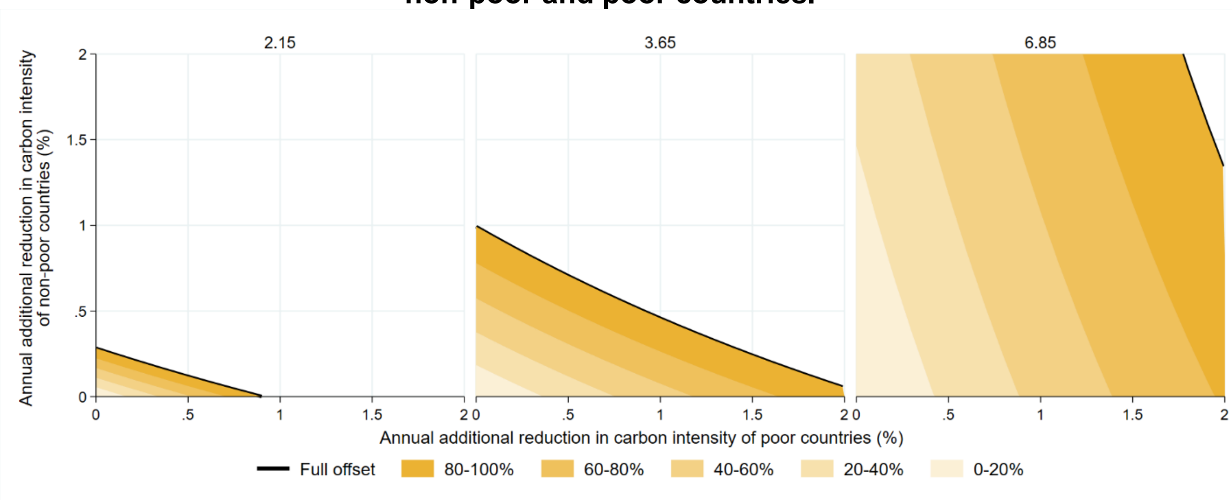
Next, we calculate the greenhouse gases for poor or rich countries each year if they become x% more carbon intensive annually (shown only for rich countries below):

$$ghgsavings_{rich}(x) = \sum_{y=2022,..,2050} \left[ghg_{rich,y} * (1-x)^{y-2022} - ghg_{rich,y} \right] \quad (13)$$

Finally, we set $ghgneeded_{world,total} = ghgsavings_{rich}(x)$ and solve for x. We do the same using poor countries instead of rich countries and at various poverty lines.

We can illustrate the relative efficacy of decarbonization in poor and non-poor countries using ISO-GHG curves (Figure 3). The ISO-GHG curves show all combinations of reductions in carbon intensity in poor and non-poor countries that would offset entirely or in part the emissions from poverty eradication. The intersection with the vertical axis (y-axis) is the reduction in rich countries equivalent to the reduction in poor countries at the intersection with the horizontal axis (x-axis).

Extened Figure 14. ISO-GHG curve of offsetting the emissions of poverty alleviation in non-poor and poor countries.



5 Parameter values for scenario analysis

In the main text, we estimate emissions increases for several different scenarios in which inequality, energy intensity of GDP, and carbon intensity of energy consumption vary. For energy intensity and carbon intensity, we use the 10th and 90th percentile of the distributions from Extended Figure 7, Panel B and Extended Figure 10, Panel B for all countries, to which we refer as the historical 'best' and 'worst' performers.

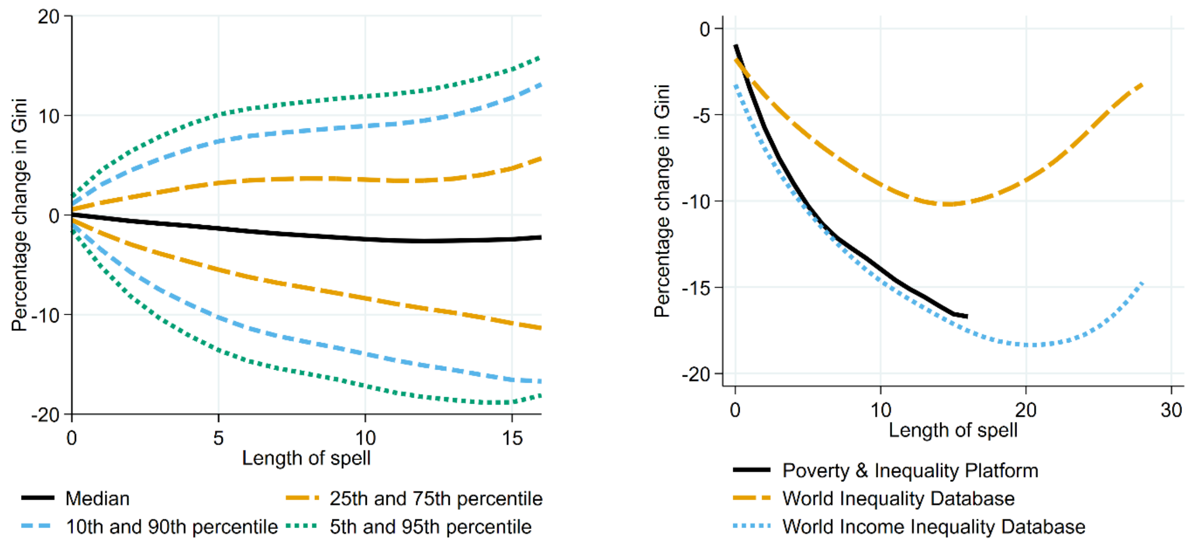
Modeling analogous changes in inequality is slightly more complicated given that we first need to derive the distribution of inequality changes observed historically. The distribution of inequality changes depends on the time period analyzed -- year-to-year changes tend to be smaller than changes observed over a decade. We look at all inequality changes observed in the World Bank's Poverty and Inequality Platform and plot them as a function of the time between the estimates. For each time period between estimates, we plot certain percentiles of the distribution of changes in the Gini. As for the other elements of the scenario analysis, the 10th and 90th percentiles will be considered our low (inequality reduction) and high (inequality rise) inequality changes. The most extreme inequality changes likely reflect either measurement error or extreme historical events (such as the fall of USSR). The inequality implications of such historical events are unlikely to be replicated systematically going forward.

Using all available historical data, over a 16-year period, the 10th percentile inequality change is equal to a reduction of the initial Gini of 17% while the 90th percentile is an increase of 13% (Extended Figure 15). There are less than 25 comparable Gini estimates 17 years apart (or more), which we use as a minimum for calculating the distribution of inequality changes. We are interested in inequality changes occurring over 28 years (from 2022 to 2050) and assume that inequality does not change further after 16 years.

Extended Figure 15: Distribution of changes in Gini coefficients

A. From the Poverty & Inequality Database

B. Comparison of 10th percentile Gini changes across databases



Note:
Source: World Bank's Poverty and Inequality Platform.

As a robustness check, we follow the same procedure as above using the World Inequality Database and the World Income Inequality Database. The World Income Inequality Database Gini changes are in line with the Poverty & Inequality Platform, in part because the latter uses the former as one of its data sources. It suggests that for periods longer than 18 years, the most optimistic inequality reductions become smaller. This may be a reflection of the type of countries that have comparable data over such long spells. The inequality changes in the World Inequality Database are much smaller. The World Inequality Database largely contains data from high-income countries and mostly uses information on inequality backed out from distributional national accounts rather than from observed consumption vectors, which is less relevant for our purposes.

In the appendix, we expand the scenario analysis by looking at different combinations of inequality changes and energy and carbon intensity, and we further vary other key modelling parameters: the population growth forecasts until 2050 and passthrough rates from GDP growth to consumption growth. Population scenarios are based on the low, medium, and high variant of the UN's Population Prospects (United Nation 2022). For the passthrough rates from GDP growth to consumption growth, we use the 10th and 90th percentile of the distribution from Extended Figure 4, Panel A for all countries. In total, we analyze 243 scenarios, which are outlined in Extended Table 4.

Extended Table 4. Parameters in different model scenarios

Parameter		Interpretation	Value
Inequality	High	90th percentile of changes in inequality (increase)	+13% in Gini in 2050
	Baseline	No change	0%
	Low	10th percentile of changes in inequality (decline)	-17% in Gini in 2050
Passthrough rate of GDP growth to consumption	High	Less growth passes through to consumption	0.44% increase in consumption for 1% growth in GDP
	Baseline	Country-specific estimate of passthrough rate	On average, 0.7% increase in consumption for 1% growth in GDP
	Low	More growth passes through to consumption	0.98% increase in consumption for 1% growth in GDP
Energy consumption per GDP	High	90th percentile of annual improvements in energy efficiency	Deteriorations in energy efficiency of 2.1% per year
	Baseline	Country-specific estimate of annual improvements in energy efficiency	On average, improvement in energy efficiency of 0.9% per year
	Low	10th percentile of annual improvements in energy efficiency	Improvement in energy efficiency of 3.2% per year
GHG emissions of energy consumption	High	90th percentile of annual improvement in GHG emissions of energy consumption (increase)	Increase in carbon intensity of energy of 2.5% per year
	Baseline	Country-specific estimate of annual improvement in energy intensity of GDP	On average, no change in carbon intensity of energy of 0.1% per year
	Low	10th percentile of annual improvement in energy intensity of GDP (decarbonization)	Reduction in carbon intensity of energy of 2.2% per year
Population growth	High	High variant of UN's population projections	Country-specific growth rate
	Baseline	Medium variant of UN's population projections	Country-specific growth rate
	Low	Low variant of UN's population projections	Country-specific growth rate

Note that for each of these scenarios, we do not only change the poverty eradication projection but also the counterfactual projection. This means that when we, for example, switch from the medium variant of population projections to a low variant of population projections, we are looking at the greenhouse gas implications of ending poverty in a world where populations grow slower. We are *not* looking at the impact of ending poverty in a world with low population growth vis-à-vis a world with no growth and medium population growth. Likewise, in the scenario with strong reductions in energy intensity, we are looking at the greenhouse gas implications of ending poverty in a world where countries reduce their energy intensity at the rate of historical best performers.

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Appendices

A Converting income distributions to consumption distributions

To convert income distributions to consumption distributions, we first take all cases in the World Bank's Poverty and Inequality Platform with both income and consumption distributions available for the same country and the same year. This concerns the cases listed in Table S1.

Table S1: Country-years with income and consumption aggregates

Albania	2016-2018
Bulgaria	2007
Croatia	2009, 2010
Estonia	2003, 2004
Haiti	2012
Hungary	1999, 2004-2007
Latvia	2004, 2007-2009
Lithuania	2004, 2008
Montenegro	2012-2014
Nicaragua	1993, 1998, 2001, 2005
Philippines	2000, 2003, 2006, 2009, 2012, 2015, 2018
Poland	1999, 2004-2018
Romania	2006-2013, 2016, 2018
Russian Federation	2014-2018
Serbia	2013, 2015, 2018, 2019
Slovak Republic	2004-2009

Source: World Bank's Poverty and Inequality Platform.

Next, we collapse each of these income and consumption distributions to 100 quantiles representing the income or consumption level at the 0.5th percentile, 1.5th percentile, etc., all the way to the 99.5th percentile. We create consumption-income pairs for each country-year-percentile. For example, the 10.5th percentile of the 2016 Albanian distribution shows that 10.5% of the population had a daily consumption less than $4.79 while 10.5% of the population had an income less than $2.83. These need not be the same people.

Plotting all pairs reveals that there are more people with very low incomes than very low consumption levels but conversely more people with very high income levels than very high consumption levels (Figure S1a). In other words, the consumption distributions tend to be more compressed.

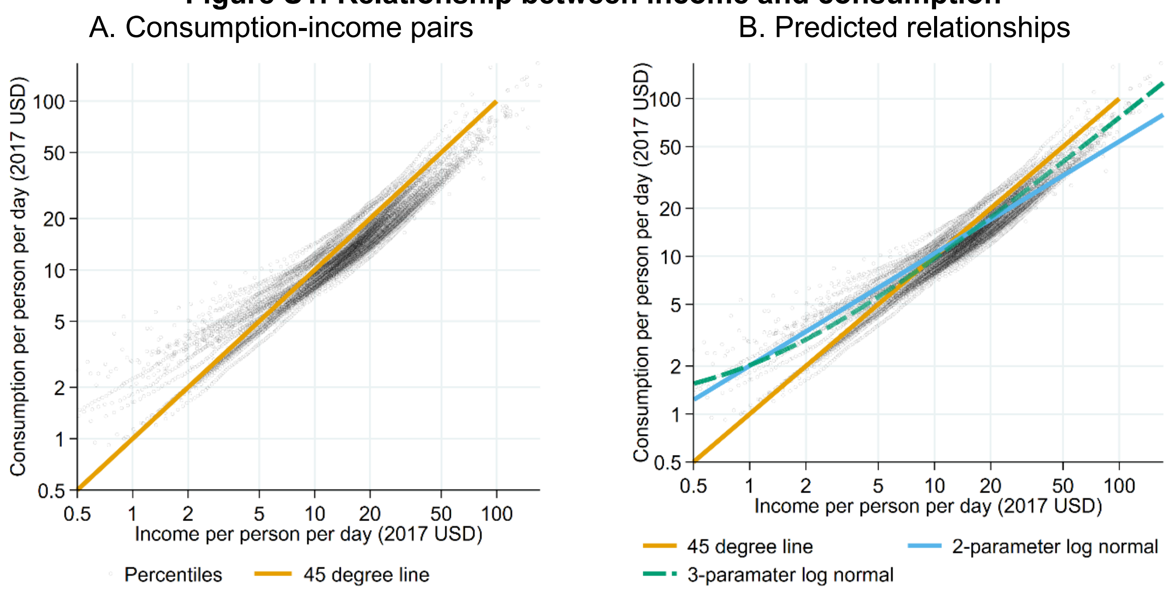
To convert income levels to consumption levels, we fit various regressions on the consumption-income percentile pairs. To be theoretically guided about what functional form to fit, we consider the functional form if both consumption and income follows distributional patterns frequently assumed. If the distributions of consumption and income are both log normal but with different mean and standard deviation, then

$$F(inc) = \frac{1}{2}\left[1 + \text{erf}\left(\frac{\ln(\text{inc}) - \mu_{inc}}{\sigma_{inc}\sqrt{2}}\right)\right]$$

$$F(con) = \frac{1}{2}\left[1 + \text{erf}\left(\frac{\ln(\text{con}) - \mu_{con}}{\sigma_{con}\sqrt{2}}\right)\right]$$

To find the relationship between income and consumption at any given quantile, we set $F(con) = F(inc)$ and isolate for $ln(\text{con})$. Doing so yields $ln(\text{con}) = \mu_{con} - \frac{\sigma_{con}}{\sigma_{inc}}\mu_{inc} + \frac{\sigma_{con}}{\sigma_{inc}}\ln(\text{inc})$. In other words, $ln(\text{con})$ would be a linear function of $ln(\text{inc})$. Fitting this regression gives an adjusted R^2 of 0.879. Yet it fails to capture the more curved relationship observed in the scatter plot (Figure S1b).

Figure S1: Relationship between income and consumption



Note: Estimated relationship between income and consumption.
Source: World Bank's Poverty and Inequality Platform.

To deal with this issue, we assume that the distributions follow the three-parameter log-normal distribution. The third parameter, γ, is a bound on the distribution above 0. If, say, it is \$1, then it means that the distribution in question only has support from that level and upwards.

$$F(inc) = \frac{1}{2}\left[1 + \text{erf}\left(\frac{\ln(\text{inc} - \gamma_{inc}) - \mu_{inc}}{\sigma_{inc}\sqrt{2}}\right)\right]$$

$$F(con) = \frac{1}{2}\left[1 + \text{erf}\left(\frac{\ln(\text{con} - \gamma_{con}) - \mu_{con}}{\sigma_{con}\sqrt{2}}\right)\right]$$

Once again setting $F(con) = F(inc)$ gives

$$\ln(\text{con}) = ln\left(\exp\left[\mu_{con} - \frac{\sigma_{con}}{\sigma_{inc}}\mu_{inc} + \frac{\sigma_{con}}{\sigma_{inc}}\ln(\text{inc} - \gamma_{inc})\right] + \gamma_{con}\right)$$

Estimating this regression through non-likelihood suggests that $\mu_{con} - \frac{\sigma_{con}}{\sigma_{inc}}\mu_{inc}$ and γ_{inc} are not statistically different from zero, so to simplify matters we set them equal to zero and are left with

$$\ln(\text{con}) = ln\left(\exp\left[\frac{\sigma_{con}}{\sigma_{inc}}\ln(\text{inc})\right] + \gamma_{con}\right) = ln\left(inc^{\frac{\sigma_{con}}{\sigma_{inc}}} + \gamma_{con}\right)$$

Both parameters of this equation have a clear interpretation. The first, $\frac{\sigma_{con}}{\sigma_{inc}}$, compares the inequality of consumption and income distributions. The lower $\frac{\sigma_{con}}{\sigma_{inc}}$, the more compressed consumption distributions are relative to income distributions. The second, γ_{con}, is the shift parameter of consumption distributions. It signifies the minimal consumption level supported. Estimating the parameters returns an adjusted R^2 of 0.965 and now clearly passes the eye test (Figure S1b). It results in the following parameters:

$$\ln(\text{con}) = ln(inc^{0.94} + 1.04)$$

One concern with the strategy adopted is that even if both consumption and income distributions follow a three-parameter log normal distribution, the joint distribution of all the country-years with income and consumption estimates at the same year need not follow a three-parameter log-normal distribution. Another concern is that the R^2 is much lower at the lower end of the distribution, which matters particularly for our exercise. For all consumption-income pairs with an income level below \$2.15 the R^2 is 0.864.

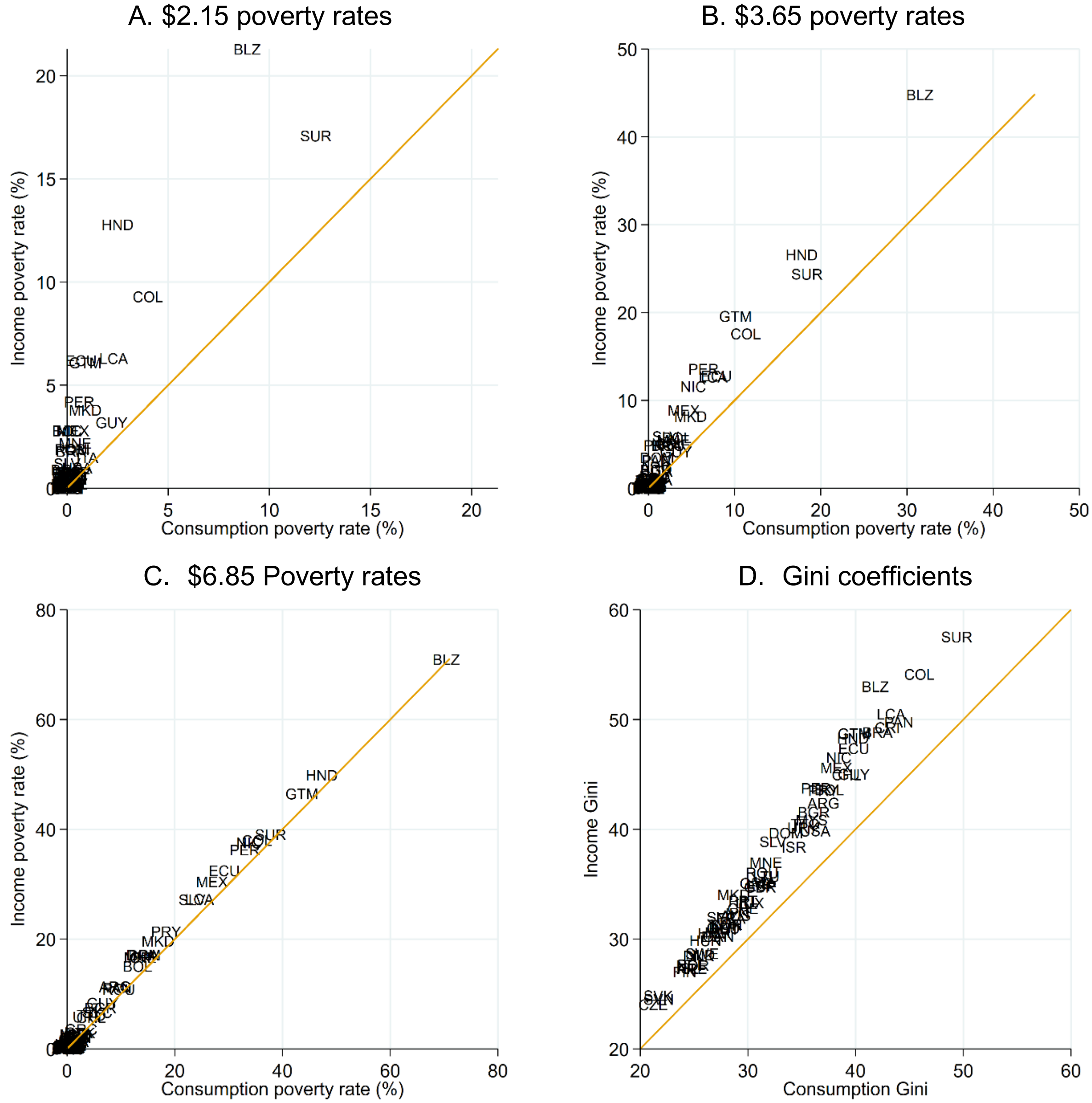
Both of these concerns can be addressed by letting the two parameters be a function of the income level of the country. In particular, one reason for the worse fit at the bottom of the distribution may be that the consumption floor, γ_{con}, varies across contexts. Even if the poorest 1% of the population of Norway and Somalia have an income less than 1\$, we may expect the poorest 1% of the two countries to have different consumption floors. In other words, the consumption floor may depend on the general income level of the country. We account for this by letting γ_{con} be a function of the median income: $\ln(\text{con}) = ln\left(inc^{\frac{\sigma_{con}}{\sigma_{inc}}} + \gamma_{0,con} + \gamma_{1,con} * \ln(inc_{median})\right)$. Fitting this model on the data yields

$$ln(inc^{0.93} + 0.68 + 0.26 * \ln(inc_{median}))$$

Hence, the consumption floor is increasing in income level. For countries with a median income around the international poverty line, the consumption floor is $0.88 = 0.68 + 0.26 * \ln(2.15)$, while for countries with a median income of \$50, it is $1.70 = 0.68 + 0.26 * \ln(50)$. Using this specification explains 17% of the previously unexplained variation below \$2.15, leaving an R^2 for this subset of 0.887. This is the final specification we use. We also tried to let the first parameter, $\frac{\sigma_{con}}{\sigma_{inc}}$, be a function of the income level of the country but found that it offered negligible gains in accuracy.

Figure S2 shows the implication of our preferred relationship for estimated poverty rates and Gini coefficients for the countries using income aggregates. Using Colombia as an example, its extreme poverty rate is 9.3% with an income aggregate but estimated to be 4% for a consumption aggregate. Its Gini goes from 0.54 with a consumption aggregate to 0.46 with an income aggregate.

Figure S2: Comparison of income and consumption poverty rates and inequality



Note: Relationship between survey-based income poverty rates and Gini coefficients, and predicted consumption poverty rates and Gini coefficients.
Source: World Bank's Poverty and Inequality Platform.

We are not the first to attempt to convert income distributions to consumption distributions. As a robustness check, we try to use the income conversion used in the World Inequality Database,[56] which likewise is based on income-consumption pairs, but works by first estimating the ratio of income to consumption as a function of the percentile:

$$\frac{inc_{pctl}}{con_{pctl}} = \alpha + \beta \frac{\ln(pctl)}{\ln(1 - pctl)}$$

With this specification, the relationship between income and consumption is unrelated to the level of income. Using this approach to first predict the income/consumption ratios and afterwards back out ln(con) for a given income level gives an R^2 of 0.772.

Another recent paper converts income distributions to consumption distributions using two boosted regression trees predicting the log ratio of mean income to mean consumption and the log ratio of the first derivative of the Lorenz curves on a set of features.[57] As far as we can tell, the authors do not report the fit of their models, so it is unclear how their results relate to ours. The World Income Inequality Database has a method to convert income Gini's to consumption Gini's but as it does not convert distributions, it is not helpful for our purposes.[58]

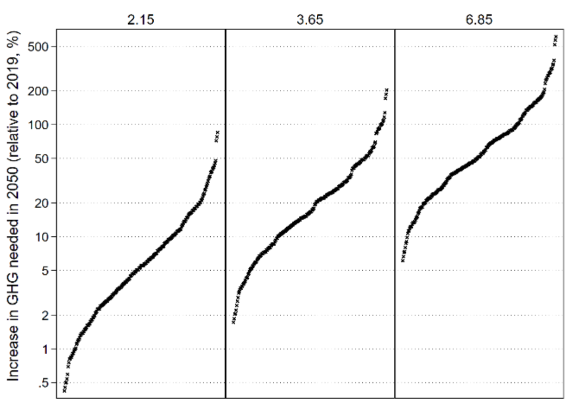
B Extended scenario analysis

In the main text, we explore the results from the baseline model plus several optimistic scenarios for declining inequality and improving energy efficiency and carbon intensity. Here, we look at a wider range of scenarios, determined by how inequality, carbon and energy intensity, and other parameters develop. For each of our main modeling parameters – population growth, passthrough rate of GDP growth to consumption, energy consumption per GDP, and CO2e emissions per energy consumption, and inequality – we model a baseline scenario as well as one low scenario and one high scenario, which correspond to the 90th and 10th percentiles of the historical parameter distributions, except for population growth where we use different UN projections (Extended Table 4).

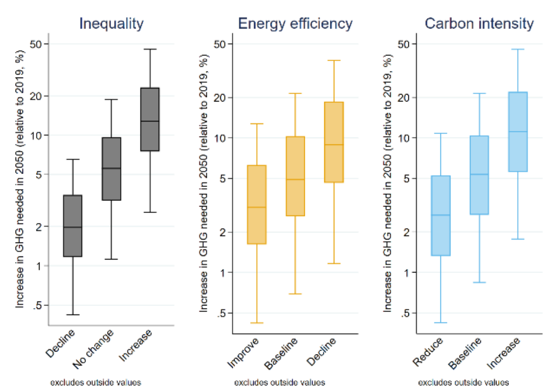
This exercise leads to 243 different scenarios for each poverty line, representing a wide range of outcomes with vastly different implications for emissions. For the extreme poverty line at $2.15, the emissions increase in 2050 relative to a scenario with no poverty alleviation ranges from 0.42% to 85%; for the $3.65 poverty line between 1.7% and 204%; and for the $6.85 poverty line between 6.12% and 611%. At all poverty lines, there are scenarios in which the emissions of poverty eradication are modest (Figure S3, panel B). At the extreme poverty line, 114 scenarios have estimated emissions increase in 2050 of less than 5%, but there are also 26 scenarios below 5% at the $3.65 poverty line, and even at the $6.85 poverty line, there are 8 scenarios with emissions increases between 5% and 10%. These optimistic scenarios, however, are contingent on combining low inequality and green growth pathways (Figure S3, panel A).

Figure S3. Extended Scenario Analysis

A. GHG increases of poverty eradication in 2050 under different scenarios at different poverty lines



B. Boxplot of GHG increases of extreme poverty alleviation in 2050 with different inequality, energy efficiency, and carbon intensity pathways



Note: Boxplots show median, 25th and 75th, and 95th and 5th percentiles

On the flipside, there are scenarios with very significant emissions increases even for extreme poverty eradication, which are combinations of rising inequality, increasing energy intensity of GDP, and increasing carbon intensity of energy. The average emissions of all extreme poverty scenarios with rising inequality are 18.7%, 15.4% with increasing energy intensity of GDP, and 17.0% with increasing carbon intensity of energy (Figure S3, panel B).