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DOI:
10.21203/rs.3.rs-376475/v2

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Article

Keywords:

Posted Date: April 18th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-376475/v2

Global mitigation efforts cannot neglect emerging emitters

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Main Text:

2648 words (excluding methods, references and figure legends)
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International efforts to avoid dangerous climate change have historically focused on reducing energy-related CO_2 emissions from countries with either the largest economies (e.g., the EU and the U.S.) and/or the largest populations (e.g., China and India). However, in recent years, emissions have surged among a different and much less-examined group of countries, raising concerns that a next generation of high-emitting economies will obviate current mitigation targets. Here, we analyze the trends and drivers of emissions in each of the 59 countries where emissions 2010-2018 grew faster than the global average (excluding China and India), project their emissions under a range of longer-term energy scenarios, and estimate the costs of decarbonization pathways. Total emissions from these "emerging emitters" reach as much as 7.5 Gt CO_2/year in the baseline 2.5° scenario— substantially greater than the emissions from these regions in previously published scenarios that would limit warming to 1.5°C or even 2°C. Such unanticipated emissions would in turn require non-emitting energy deployment from all sectors within these emerging emitters, and faster and deeper reductions in emissions from other countries to meet international climate goals. Moreover, the annual costs of keeping emissions at the low level are in many cases 0.2%-4.1% of countries' GDP, pointing to potential trade-offs with poverty reduction goals and/or the need for economic support and low-carbon technology transfer from historically high-emitting countries. Our results thus highlight the critical importance of ramping up mitigation efforts in countries that to this point have been largely ignored. [*245 words*]

Fossil fuel carbon dioxide (CO_2) emissions are the main cause of global warming. Since the 1990s, analyses of fossil fuel CO_2 emissions have focused on a handful of industrialized economies where emissions have been high (the U.S.[1] and EU[2]) along with populous and rapidly-industrializing countries such as China and India[3,4]. Integrated Assessment Models (IAMs) aggregate the world into regions based on geography and economic development such that low- or middle-income countries with historically small emissions have been typically included in large and undifferentiated groups such as "other Africa" or "Rest of World (ROW)"[5,6]. However, most of the growth in global emissions since 2010 has been among these "ROW" countries. For example, most of the 59 countries whose annual emissions grew faster than the global nations' average 2010-2018 (hereinafter "emerging emitters") were developing economies, including many low-income countries[7,8]. Although none of these emerging emitters are individually large sources of emissions today, their combined emissions are greater than any single country except China and the U.S., and 65% greater than India's annual emissions in 2018 (the world's third largest emitter). Thus, the success of international mitigation efforts may hinge upon these emerging emitters and whether their goals of economic growth and human development are achieved using fossil energy.

Here, therefore, we systematically assess recent trends of emissions and their drivers among the 59 emerging emitters (defined as countries whose annual emissions 2010-2018 grew at or faster than the 2% per year average of all nations', but excluding China and India); project these countries' future emissions under scenarios that span a range of long-term socioeconomic and energy system trajectories; and assess the economic and climate implications of our scenarios. Details of our analytical approach and datasets are provided in the *Methods*. In summary, we characterize the drivers of each of the 59 countries' emissions by decomposing fossil fuel CO_2 emissions data from the International Energy Agency (IEA), and then disaggregate the countries from the regional groupings in Shared Socio-economic Pathways (SSPs) developed by the MESSAGEix-GAINS IAMs[9,19,20] and re-project their emissions for the period 2020-2050 based on recent trends of their emissions and energy systems and a range of mitigation efforts. We then evaluate the implications of emissions in our new scenarios for international climate targets and the economic and energy pathways of the emerging emitters.

Emerging emitters

Fig. 1 compares the percent changes 2010-2018 in annual CO_2 emissions and GDP (Gross Domestic Production) among the 59 emerging emitters (listed in Table S1; see Supplementary Figs. 1-2 for emissions by fuel type and by sector). The average annual growth rate of emissions of the 59 countries 2010-2018 was 6.2%—much higher than the 2.0% average of all nations worldwide, and also higher than the 4.6% annual growth rate of these same countries' GDP, reflecting increasing use of fossil energy (i.e. carbonization) of their economies. Located in Asia, Africa, and Latin America, individually these countries emitted between 0.7 and 542.9 Mt (million tons) CO_2 in 2018 (bounded by Eritrea and Indonesia, respectively; Fig. 1). However, together the countries' annual emissions grew by 40.7% over the period, from 2.7 Gt (gigatons) to 3.8 Gt CO_2. In comparison, emissions in China, the U.S., and India were 9.6, 4.9, and 2.3 Gt CO_2 in 2018. Moreover, the 1.1 Gt increase in emissions accounts for 38.9% of the global increase in emissions over the period.

The emerging emitters include countries in development categories ranging from the least developed country (LDC) to economy in transition (EIT)[8], but in most cases with GDP per capita substantially less than the global average (in 53 of the 59 countries per capita GDP was less than \$11,000/yr in 2018 (constant 2010 USD). In 2017 the countries were also home to 698 million people in absolute poverty (e.g. < 1.9 US\$ per day in purchasing power parity value)—9.3% of global population in that year[10]. Among the 59 countries, emissions grew faster than GDP in 34 (58%), and *twice* as fast as GDP in 12 of these (20%; Fig. 1). In 25 others (42%), economic growth outstripped emissions growth, corresponding to decreasing carbon intensity of those economies.

Drivers of recent emissions surge

Figure 2 shows the drivers of changes in emissions 2010-2018 for 20 emerging emitters in Africa, Latin America and Asia. Supplementary Figures 3-6 show analogous plots for the other 39 countries. In each case, we plot the 2 most influential drivers of changes in emissions over the 8 year time period. Across all 59 emerging emitters, population growth (red bars) is most important in 17 (29%) of the countries including Uganda (Fig. 2a) and Lebanon (Fig. 2d), though increases in GDP per capita (dark blue) are the most important factor underlying emissions increases in 26 (44%) of the countries including Ethiopia, Colombia and Vietnam (Figs. 2e, 2f and 2g). Following closely behind these socioeconomic factors are increases in use of a particular fossil fuel; increases in either oil (orange) or coal (light orange) are the main drivers of emissions increases in 8 of the 59 countries (14%), including Sudan, Haiti, Myanmar, Guatemala and Kyrgyzstan (Figs. 2i, 2j, 2k, 2b, and 2n, respectively; for emissions by fuel type, see Supplementary Fig. 3). Energy intensity (turquoise) increases drove 7 (12%) of the countries' emissions growth as the top-two drivers, including Algeria and Laos (Figs. 2m and 2o). Increases in the CO_2 intensity of energy use were also the key driver of emissions increases in a handful (3 or 5%) of the countries', including Nicaragua, Botswana and Nepal (Figs. 2q, 2r, and 2s, respectively). Less commonly, increases in share of value added in GDP represented by industry (black) were also important, such as in Ethiopia (Fig. 2e) and Haiti (Fig. 2j).

In contrast, the factors most important to suppressing growth of emissions in these countries are declining energy intensity (in 19 or 32%), decreases in CO_2 intensity of energy use (in 12 or 20% of the countries), decreases in the share of value added by industry (in 9 or 15% including many Latin American and Other Asian; Fig.2f, 2n, 2h, and 2t), and decreases in the share of oil energy (in 9 or 15%, including Botswana and Nepal). We describe the drivers of case countries' emissions in greater detail in Supplementary Information and Supplementary Figs. 7-12.

Projections of future emissions

Among the 59 emerging emitters, a major policy priority is economic development to increase incomes and reduce poverty. In turn, GDP per capita is routinely a key driver of emissions increases (Fig. 2). Without offsetting decreases in the carbon intensity of these countries' economies, such development can therefore be expected to spur future growth of emissions. Inertia of emissions from new and historically long-lived energy infrastructure is also a factor in many of these countries[11]. Long-term trajectories of emissions of the emerging emitters will thus be determined by development and energy pathways, and especially of fossil fuel-based power, industry, transportation and residential sectors. Figure 3 shows total emissions and shares of non-emitting energy sources from all emerging emitters under a range of scenarios (Fig. 3a; Data S2). In each case, these projections include four sector groupings (power, industry, transportation, and residential sectors) and assume that the share of non-emitting energy used in each sector (i.e. solar, wind, or nuclear energy sources) increases at different rates. Specifically, the 2.5° scenario assumes no deployment of non-emitting energy 2020-2050 (Fig. 3e; consistent with regional projection by the GAINS model for the RCP4.5 pathway and New Policy Scenario) and would put the world on track to warm 2-3° by 2100 if other countries around the world follow the same pathway; the 2.2° scenario assumes that the capacity non-emitting energy sources grows by 8.8%/year and tracks toward 2-2.4° of warming by 2100; the 2° scenario assumes 10.5%/year growth in non-emitting energy sources and is consistent with the goal of limiting 2° of warming in 2100; and the 1.5° scenario assumes the deployment of non-emitting energy increases 11.2%/year is consistent with the goal of limiting 1.5° of warming in 2100. These scenarios thus span a wide range of mitigation efforts among emerging emitters, from zero to aggressive deployment of low-carbon energy technologies in all sectors (see *Methods*).

Under the 2.5° scenario, total emissions from the 59 emerging emitters continue rising and reach 7.8 Gt in 2050, with cumulative emissions of 180 $GtCO_2$ 2020-2050 (Fig.3a). In the other three scenarios, emissions from emerging emitters increase 2020-2035 and then decline to reach varying levels by 2050. Emissions are 3.6, 1.2 and 0.1 $GtCO_2$/year in 2050 in the 2.2°, 2°, and 1.5° scenarios, respectively, reflecting reductions relative to the 2.5° scenario of 54.1%, 84.2%, and 98.8%, respectively. In all scenarios, the power sector is the largest contributor to cumulative emissions (40.6%-42.2%), followed by industry (26.8%-29.4%), transportation (19.4%-24.5%) and residential (8.4%-8.9%) sectors (Figs. 3a-3d).

Scenarios with greater emissions reductions correspond to those with more rapid deployment of non-emitting energy technologies (e.g., renewable generation, nuclear power, and biofuels) among emerging emitters. In the 2.5° scenario, non-emitting power capacity remains nearly constant at 2020 levels (average annual change 2020-2050 of -0.1%; Fig. 3e). In the mitigation scenarios, non-emitting power capacity increases by an average of 5.3%, 6.9%, and 7.5% annually, but this rate increases considerably if industry, transportation, and residential energy demand is also electrified, to as high as 11-12% in the 2° and 1.5° scenarios and depending on the availability of biofuels (darker red curves in Figs. 3g and 3h; in cases with biofuels, the energy mix of electricity and biofuels economy-wide is held constant at 2019 levels). Whether by electricity or carbon-neutral biofuels, large shares of residential, industrial and transportation energy come from non-emitting sources by 2050 in the 2.2°, 2°, and 1.5° scenarios (Figs. 3j, 3k, and 3l), especially in the industry and transportation sectors (residential sector in emerging emitters was already dominated by biofuels in 2018). In the 1.5° scenario, the share of non-emitting energy reaches 100% for all sectors by 2050.

Figure 4a represents cumulative emissions from emerging emitters 2020-2050 as a function of annual growth in the countries' GDP versus annual growth in non-emitting sources of energy (Fig. 4a). For example, if GDP among emerging emitters grows at 5.8% per year as projected in SSP2-4.5, cumulative emissions 2020-2050 are 180 $GtCO_2$ in the 2.5° scenario, decreasing to 131, 112, and 103 $GtCO_2$ in the 2.2°, 2°, and 1.5° scenarios, respectively (red, yellow, and green circles in Fig. 4a). But the temperatures assigned to our scenarios assume that the rest of the world is mitigating accordingly, and there are trade-offs between emerging emitters and countries in the rest of the world if that is not the case (Supplementary Fig. 13). Figure 4b shows how much faster countries in the rest of the world would need to reduce their emissions depending on what path emerging emitters follow. For example, if emerging emitters follow our 2.5° scenario (i.e. their emissions increase 2.4%/year), stabilizing global temperatures at 1.5° would require countries in the rest of the world to decarbonize at 7.2%/year (at the median of budgets[12]), as opposed to 4.2%/year if emerging emitters are also on the 1.5° scenario (i.e. their emissions decrease 11.6%/year; Fig. 4b). Yet the decarbonization rates required in other countries to meet international climate targets are not particularly sensitive to changes in the rate of decarbonization in emerging emitters beyond ~6%/year; cumulative emissions from emerging emitters are very similar under the 2° and 1.5° scenarios and in both cases are small compared to global budgets (Fig. 4a).

Using projected costs from the literature[13], we estimate that the annual costs of keeping emissions at the 1.5° scenario are in many cases 0.2%-4.1% of countries' GDP, and the cost of non-emitting sources of electricity (i.e. renewable or nuclear generation) in our 1.5° scenario represents a median of 4.9% of projected annual GDP of emerging emitters in 2050 (1.2%-14.4%; $P<0.05$; see Supplementary Fig. 14); for the 2° scenario, the share decreases slightly to 4.4% (1.1%-13.6%; $p<0.05$). For example, the median cost of replacing fossil fuels with non-emitting energy would cost Ethiopia 11.0% of its GDP in 2050. Costs per ton of emissions avoided increase from \$240.3 per tCO_2 in the 2.2° scenario to \$239.2 and \$249.9 per tCO_2 under the 2.0° and 1.5° scenarios, respectively, with cumulative costs 2020-2050 of \$42.3-57.8 trillion (Fig. 4c), i.e. 0.6%-0.8% of the global GDP over the period. These costs can be paid domestically or from financial transfers from high-income regions.

Discussion and conclusions

None of the countries we identify as emerging emitters emit more than 2% of global emissions in recent years, but together they have dominated the growth of such emissions over the past decade and will have an important influence of cumulative fossil emissions this century. In particular, as these countries recover from the COVID pandemic, their economic development and investments in energy infrastructure are likely to set the carbon intensity of their economies for decades to come[14]. Indeed, our results suggest that the longer-term trajectories of emissions will depend upon climate and energy policies as economic growth in these countries' resumes. Yet sustained economic growth, crucial for poverty reduction, as well as projected increases in population will continue to drive growth in CO_2 emissions in these countries, even assuming rapid deployment of non-emitting energy across all sectors. Given their importance and unique circumstances, future projections and energy-emissions models would do well to disaggregate "Rest of World" regions and resolve country-specific pathways.

Reductions in these countries' future emissions depend on rapid deployment of non-emitting energy in all sectors. Yet we have shown that the benefit of increased ambition among emitters has diminishing returns in our scenarios; the rate of emissions reductions required in other countries of the world is reduced much more by shifting emerging emitters from a 2.5° scenario to a 2.0° scenario than it is by shifting from a 2.0° to 1.5° scenario. Moreover, the costs of ambitious mitigation are large, representing >4% of projected GDP in 2050. But these costs must be compared to the costs of instead meeting rising energy demand with fossil fuel energy, as well as the cost per ton of emissions avoided in other regions, e.g., the annual GDP loss to reach 1.5°C-target emissions in Japan is estimated as high as 4.5%[15]. Making such comparisons suggests that, although daunting, mitigation among emerging emitters may be cost-effective, and further makes the case for economic support and technology transfer from higher-income countries on the basis of both human development and meeting climate goals.

Methods

Emission drivers: index decomposition analysis.

We divide the emissions growth (C) over 2010 to 2018 into contributions of six drivers: C_P from population (P) growth; C_G from economic growth measured by GDP per capita (GPC); C_{IS} from industrial structure (IS), as the share of GDP of primary industry, secondary industry, and tertiary industry; C_{EI} from energy intensity (EI) that is energy consumption (E) per unit of GDP; C_{ES} from energy structure (ES), as the share of consumption of energy types including coal, oil, natural gas, and other types; and C_{CI} from CO_2 emissions intensity (CI) that is emissions per unit of energy consumption, as follows:

$$C = \sum_{ij} P \times \frac{G}{P} \times \frac{G_i}{G} \times \frac{E_i}{G_i} \times \frac{E_{ij}}{E_i} \times \frac{C_{ij}}{E_{ij}} = \sum_{ij} P \times GPC \times IS_i \times EI_i \times ES_{ij} \times CI_{ij}$$

Where, *i* refers to the *i*th industry in primary industry, secondary industry, and tertiary industry; *j* refers to the *j*th energy type in coal, oil, natural gas, and other types. The change in C from time 0 to time T can be divided into six parts using logarithmic mean Divisa index (LMDI) method[16,17] as follows:

$$\Delta C = C^T - C^0 = \Delta C_P + \Delta C_{GPC} + \Delta C_{IS} + \Delta C_{EI} + \Delta C_{ES} + \Delta C_{CI}$$

where:

$$\Delta C_X = \sum_{ij} \frac{C_{ij}^T - C_{ij}^0}{\ln C_{ij}^T - \ln C_{ij}^0} \times \ln\left(\frac{X_{ij}^T}{X_{ij}^0}\right)$$

where, X_{ij} refers to the driving factors, i.e. P, GPC, IS_i, EI_i, ES_{ij}, and CI_{ij}.

Emission scenario settings for over 2020-2050.

In each case, these projections include four sector groupings (power, industry, residential and transportation) and assume that energy demand in each sector becomes non-emitting at certain annual growth. Specifically, we develop four scenarios for each sector grouping: a 2.5° baseline scenario that assumes no deployment of non-emitting energy over 2020-2050, i.e., the emitters follow the RCP 4.5 and SSP2 pathway of development and reach the 2050 emission target of global warming of 2~3 degree by 2100; a “2.2° ambition” scenario, in which the deployment of non-emitting energy grows by 8.8% annually over the period and reach the 2050 emission target of global warming of 2~2.4 degree by 2100; a “2-degree ambition” scenario, in which the deployment of non-emitting energy grows by 10.5% annually over the period and reach the 2050 emission target of global warming below 2 degree by 2100; and a “1.5° ambition” scenario that assumes the deployment of non-emitting energy grows by 11.2% annually over the period and reach the 2050 emission target of global warming below 1.5 degree by 2100.

Emissions accounting over 2020-2050

Country-level CO_2 emissions trend for three scenarios in 2020-2050. We selected the SSP2 baseline scenario (middle of the road) with no new policy consideration developed by IIASA's MESSAGEix[18] and imported into GAINS model(based on the default storyline of SSP2_45 of GAINS)[9,19,20] to provide CO_2 emissions and energy mix projections for the 59 emerging emitters for our 'BAU' scenario. However, the GAINS model only covers major countries and regions, while more than half of emerging emitters studied here are aggregated into 'Other Regions'. Among 59 emerging emitters, there are 24 countries' SSPs are available in GAINS database. For 35 out of 59 countries that future socioeconomic development trajectories are not available, thus, the downscaling and appropriate calibration approaches are used to project country-level emissions, according to the region-level emissions. We present all projected emission data 2020-2050 in Supplementary Table S2. We also provide full comparison between our calibrated data and direct downscaling data from SSPs produced by different IAMs (see Supplementary Fig. S15).

We conduct the following procedures to calibrate the historical CO_2 emissions and emissions after 2020. As shown in Equation 1, scenario settings (by sector and by different low carbon technology deployment) are applied to GAINS regional energy consumption to get emissions of region *r* under scenario *base* ($Em_{t,r,base}$). The ratio of $Em_{t,r,base}$ to $Em_{2020,r,base}$ shows a relative change of year *t* to 2020 under scenario *base*. Applying that relative change to the country historical emissions ($Em_{2020,c,history}$) and we get the downscaled and calibrated emissions projected of country *c* and scenario *base*. By similar way we obtain the emissions trajectories of 1.5° and 2° targets.

$$Em_{t,c,base} = Em_{2020,c,history} \times \frac{Em_{t,r,base}}{Em_{2020,r,base}} \qquad \text{Equation 1}$$

The emissions under the 2.2° ambition, 2° ambition, and 1.5° ambition scenarios are modified based on the sectoral energy demand and non-emitting energy deployment of each designed scenario. For scenario *s*, the emissions of sector *i* in year *t* are calculated by the fossil fuel demand, $Ene_{ff,i,t,s}$, and corresponding emission factors, EF_{ff}. With the non-emitting energy *j* (which can be renewable energy or nuclear) growing at an annual growth rate of $g_{i,j}$, the fossil energy demand gets substituted by non-emitting energy. Therefore, the total emissions at thin year are:

$$Em_{t,s} = \sum_i Em_{i,t,s} = \sum_i Ene_{ff,i,t,s} \times EF_{ff}$$
$$= \sum_i \left(Ene_{i,t} - \sum_j Ene_{i,j,t,s} \right) \times EF_{ff}$$
$$= \sum_i \left[Ene_{i,t} - \sum_j Ene_{i,j,2021,s} \times \left(1 + g_{i,j,s}\right)^{t-2021} \right] \times EF_{ff} \quad \text{Equation 2}$$

Where the $Ene_{i,t}$ represents the energy demand in sector *i* in year *t*, $Ene_{i,j,2021,s}$ is the non-emitting energy of sector *i* in 2021 under assumptions of scenario *s*. $Ene_{i,j,2021,s}$ is set by the newly added fossil energy demand in 2021, while if that is zero or negative, $Ene_{i,j,2021,s}$ is determined based on the targeted fossil energy in 2050 and the average $g_{i,j,s}$ for scenario *s*:

$$Ene_{i,j,2021,s} = \begin{cases} Ene_{ff,i,2021} - Ene_{ff,i,2020}, & Ene_{ff,i,2021} > Ene_{ff,i,2020} \\ \dfrac{Ene_{i,2050} - Ene_{ff,i,2050,s}}{\left(1 + \overline{g_{i,j,s}}\right)^{29}}, & Ene_{ff,i,2021} \le Ene_{ff,i,2020} \end{cases} \quad \text{Equation 3}$$

Since non-emitting energy refers to biofuels combustion and renewable and nuclear power, the demand for non-emitting power capacity is composed of that from the power sector only and all sector demand. Therefore, Fig.3e-3h show the non-emitting power demand of the power sector only, the non-emitting power demand of all sectors electrified (but biofuels also deployed as non-emitting energy), and the non-emitting power demand of all sectors using non-emitting power without biofuels.

<u>Economic costs estimation for four scenarios</u>

We estimated the economic costs of the deployment of CCS and renewable energy for the power sector in emerging emitters for the 2.2° ambition, 2-degree ambition, and 1.5° ambition scenarios. For renewable energy and nuclear power generation technology, the technology cost is forecast[13] using the Stochastic Exponent Method as:

$$y_{t+1} = y_t \left(\frac{X_{t+1}}{X_t} \right)^{-W_{t+1}} \quad \text{Equation 4}$$

Where, y_t is the technology cost in year t, X_t is cumulative production and W is the Wright exponent (or learning exponent). In this case, the compound average annual growth rate (CAAGR) of global cumulative electricity generation over the most 5 years is used to specify a future deployment scenario for 2020-2030 projection, except for the PV and wind 2030 forecasts, where we used the CAAGR of cumulative electricity generation in China observed over the most recent 5 years instead. While for 2030-2050 projection, the CAAGR of cumulative electricity generation in China to reach carbon neutrality is used. This method implicitly assumes that deployment, R&D funding, and other variables continue on their recent historical trajectories for the entire duration of the forecasting period.

Renewable energy and nuclear energy for power generation is assumed in the four scenarios for non-thermal power dominated countries. Since the non-fossil energy generation takes a tiny percentage in the global market, in the four scenarios, we assume the costs of renewable and nuclear energy generation are identical across the world, and the deployment grows at the rate of that in China to reach carbon neutrality by 2060. Based on the projected costs of six types (r, including wind, solar, geothermal, biomass power, hydropower and nuclear) of renewable and nuclear energy for power generation per kWh per year ($y_{i,t,r}$), the total costs of renewable and nuclear energy for power generation for country i under scenario s in year t are the sum of the costs of the newly built power units, $Cost\_REN\_new_{i,s,t}$, and that of the existed ones, $Cost\_REN\_existed_{i,s,t}$:

$$Cost\_REN_{i,s,t} = Cost\_REN\_new_{i,s,t} + Cost\_REN\_existed_{i,s,t} \qquad \text{Equation 5}$$

Suppose the renewable and nuclear power units generate equal power each year, the annual operating costs remain the same as that of the first year, $Cost\_REN\_new$. The existing power units' costs, $Cost\_REN\_existed_{i,s,t0}$, is the sum of the annual operating costs of all the formerly built units (Equation 5). Since the lifecycle of renewable and nuclear power units is usually longer than 20 years, the renewable power units remain in operation during 2020-2050.

$$Cost\_REN\_existed_{i,s,t0} = \sum\nolimits_{t<t0} Cost\_REN\_new_{i,s,t} \qquad \text{Equation 6}$$

Newly added energy capacity is partly or fully supplied by renewable and nuclear energy generation. The costs are product of per unit cost $y_{i,t,r}$ and the power generation. By assuming the renewable energy mix as the same as that in 2019 ($\frac{Ene\_REN_{2019,r}}{Ene\_REN_{2019}}$), using the newly added energy capacity $Ene\_new_{i,s,t}$, and the deployment of renewable energy generation $Deployment_{i,s,t}$, the total costs of the newly added renewable power generation can be estimated as:

$$Cost\_REN\_new_{i,s,t} = \sum\nolimits_{r} y_{i,t,r} \times \frac{Ene\_REN_{2019,r}}{Ene\_REN_{2019}} \times Ene\_new_{i,s,t} \times Deployment_{i,s,t} \qquad \text{Equation 7}$$

Historical data 2010-2018.

CO_2 emissions from fuel combustions and energy consumption data over 2010-2018 are from the International Energy Agency (IEA)[7,21], covering data of over 140 countries by energy type and economic sector. The population and the GDP data, and the industrial structure data, i.e. the percentage of agriculture, forestry, and fishing, industry and services in value added are from the World Bank[22].

Data for 2019-2050.

The CO_2 emissions data 2019 are linearly extrapolated based on data 2010-2018, and the CO_2 emissions 2020 are collected from work of Le Quéré et al. Nature Climate Change (2020)[23]. The BAU assumption data including energy mix data and CO_2 emissions data are from the "New Policies Scenario" (NPS) projections of GAINS model from IIASA[9]. The CO_2 emissions data, the population data, and the GDP data under SSPs are from the SSP Database (version 2.0)[24–29].

Data for global warming of 1.5°C and 2°C.

The CO_2 emissions data of countries under the 1.5°C and 2°C global warming scenarios are compiled from the Integrated Assessment Modeling Consortium (IAMC) 1.5°C Scenario[30]. The used data include the CO_2 emissions of the world under 1.5°C and 2°C scenarios. For the emissions of the 59 emerging emitters, we use the emissions under the BAU scenario. The emissions of the rest of the world are defined as the emissions of the world minus that of the 59 emerging emitters.

Acknowledgments

Funding

This work was supported by the National Natural Science Foundation of China (41921005, 41991312).

Author contributions

Conceptualization: DG, SJD

Methodology: CC, DW, JM, SZ, YS

Visualization: CC, SJD

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Writing – review & editing: CC, DG, DW, VC, PB, SZ, SJD

Competing interests

Authors declare that they have no competing interests.

Data availability

Historical data 2010-2018: CO_2 emissions from fuel combustions and energy consumption data over 2010-2018 are from the International Energy Agency (IEA)[7,21], covering data of over 140 countries by energy type and economic sector. The population and the GDP data, and the industrial structure data, i.e. the percentage of agriculture, forestry, and fishing, industry and services in value added are from the World Bank[22]. Data for 2019-2050: The CO_2 emissions data 2019 are extrapolated based on data 2010-2018, and the CO_2 emissions 2020 are collected from work of Le Quéré et al. Nature Climate Change (2020)[23]. The BAU assumption data including energy mix data and CO_2 emissions data are from the "No Policies Scenario" (NPS) projections of GAINS model from IIASA that developed based on IEA's world energy outlook 2018[9]. The CO_2 emissions data, the population data, and the GDP data under SSPs are from the SSP Database (version 2.0)[24–29]. Data for global warming of 1.5°C and 2°C: The CO_2 emissions data of countries under the 1.5°C and 2°C global warming scenarios are compiled from the Integrated Assessment Modeling Consortium (IAMC) 1.5°C Scenario[30]. The used data include the CO_2 emissions of the world under 1.5°C and 2°C scenarios. The comparison between the projections of this work and the SSPs data is shown in Fig. S14 and Data S2. All data are available in the main text or the supplementary information.

Data availability

All the codes associated with this paper are available from the corresponding authors upon reasonable request.

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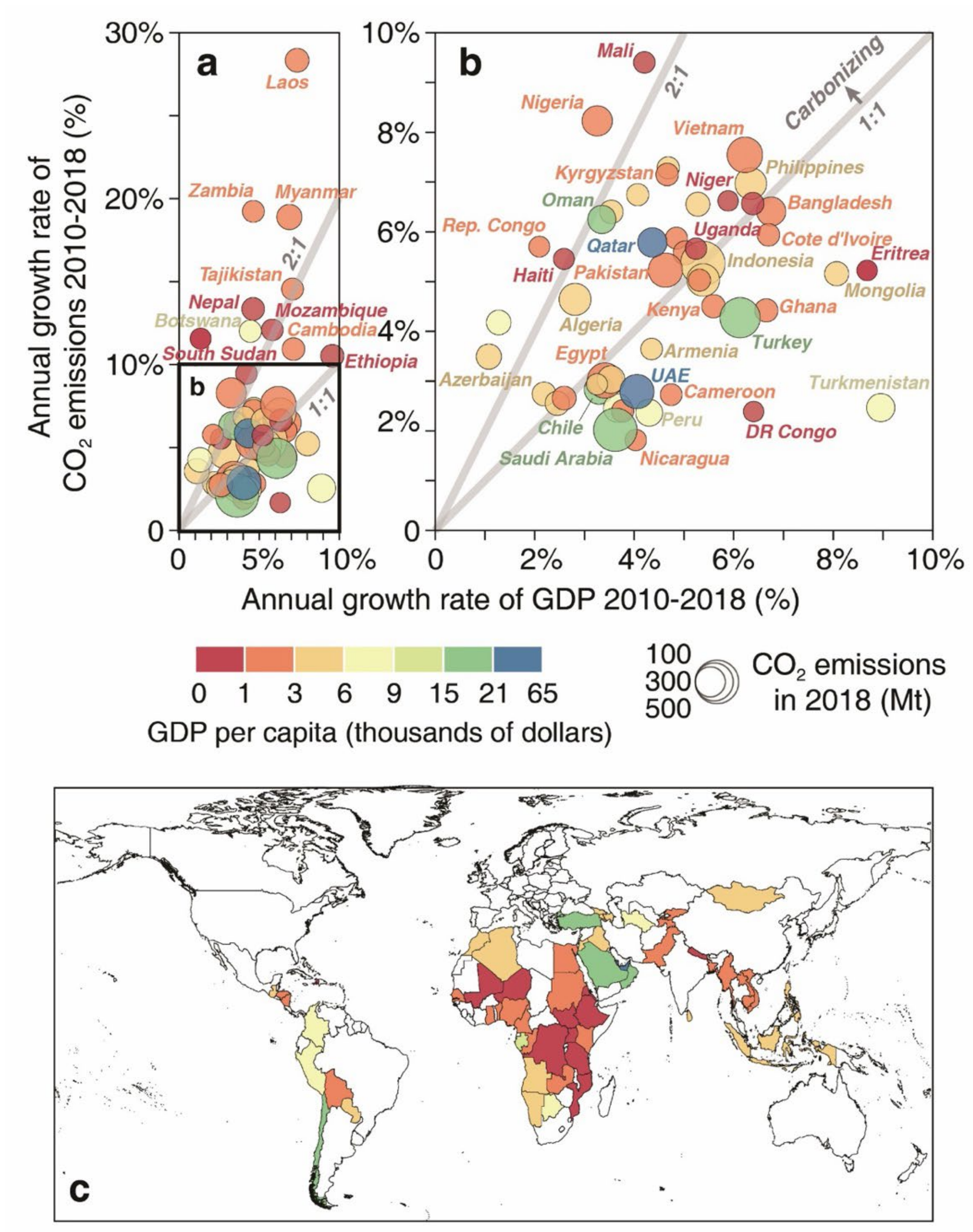

Fig. 1. Relative increase of CO_2 emissions and GDP in 2018 over 2010. Relative increase of GDP and CO_2 of the 59 countries (due to lack of data, data presented for South Sudan are based on 2012-2015, Eritrea on 2010-2011, and DR Congo on 2010-2017, respectively) with fast-growing emissions in 2018 over levels of 2010 are shown in the panel (a). Each bubble represents a country, plotted by GDP increase in 2018 relative to the level of 2010 on the horizontal and relative CO_2 emission increase on the vertical. The bubbles of countries with a less-than-100% emission increase (within the black dashed box) in the lower left part are zoomed in on the right panel (b). The two grey lines with slopes of 1 (lower) and 2 (upper) mean the CO_2 emission growth rate is the same as or twice the rate of the GDP growth. Countries plotted above the 1:1 line are carbonizing. The size of the bubbles represents the amount of CO_2 emissions in 2018. The colors represent the per capita GDP of the countries, red for the lower and blue for the higher, with the same color shown in the map (c).

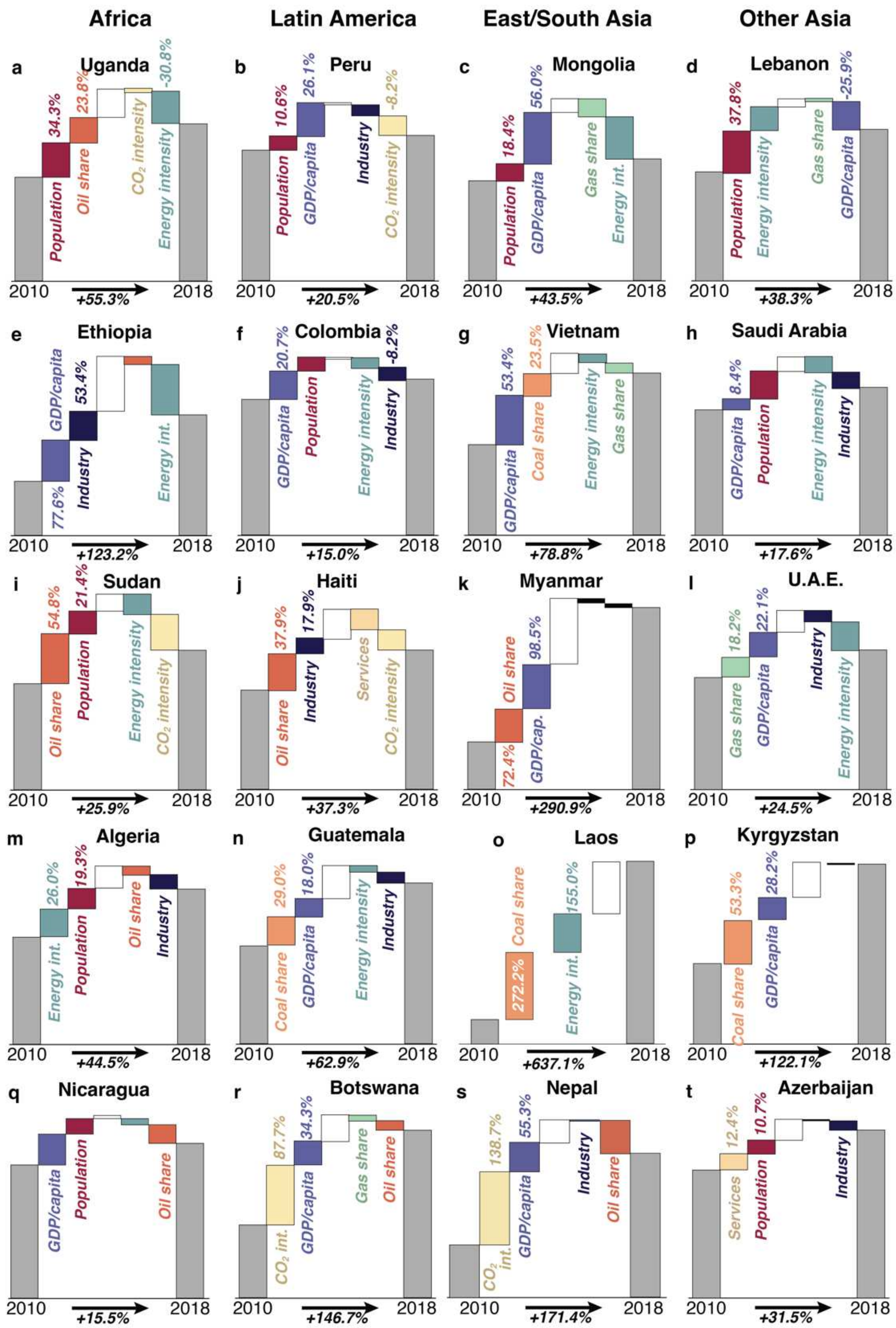

Fig. 2. Case countries with surging emissions and their drivers. The waterfalls show the drivers of emission growth over 2010-2018, including drivers increasing consumption (population, GDP per capita), drivers affecting economic structure (industrial structure, i.e. share of the value added of primary, secondary, and tertiary industry, and the energy intensity of GDP), and drivers affecting carbon intensity (energy structure, i.e. share of consumption of coal, oil, natural gas and other fuel, and CO_2 emission intensity of energy). Each country has their two main drivers and two main inhibitors shown, and the relative change of emission increased from the level of 2010 to that of 2018.

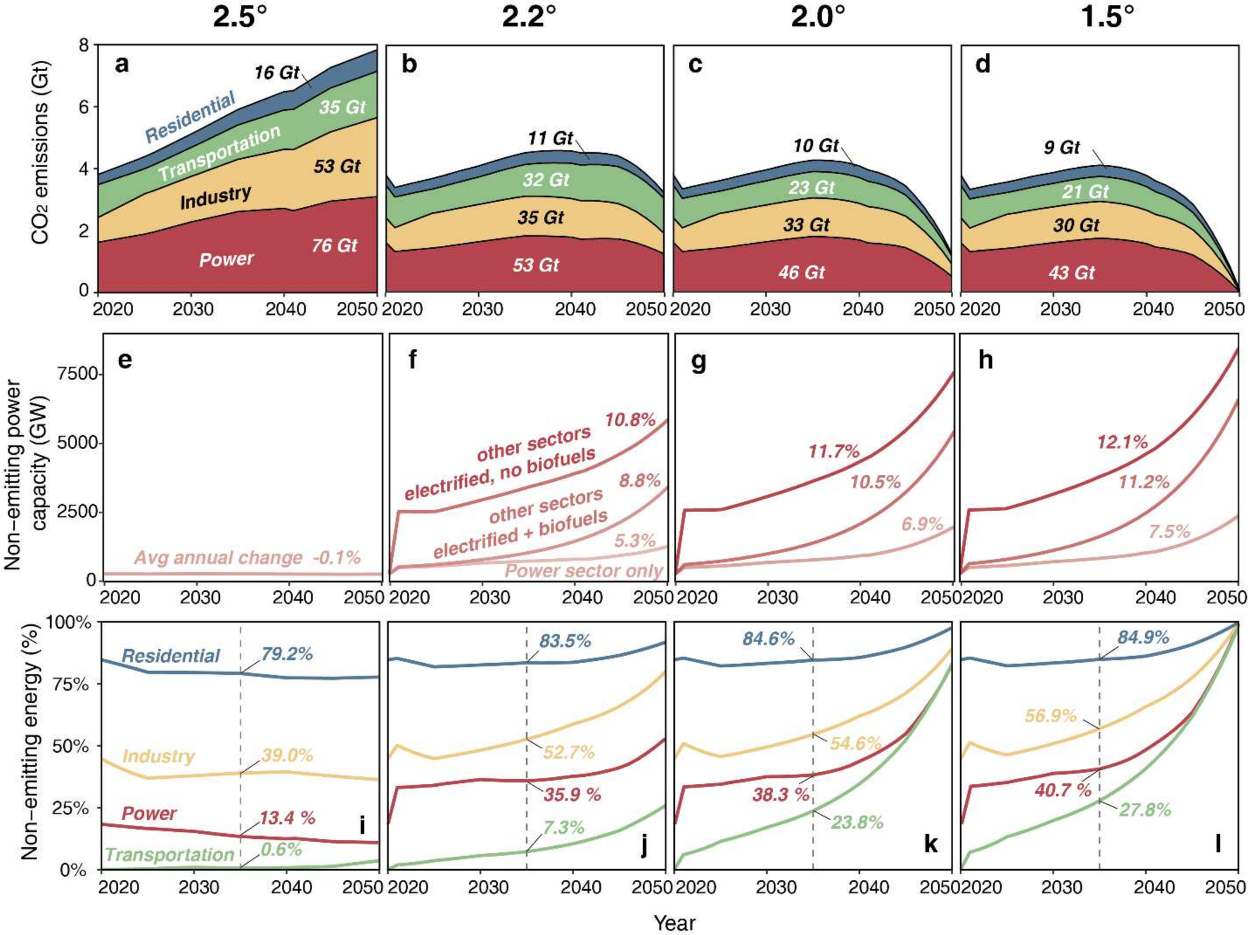

Fig. 3. Projected emissions, non-emitting power capacity and non-emitting energy share of sectors and scenarios. Emissions projections under the scenarios of 2.5° baseline, 2.2°, 2.0° and 1.5° are shown in (a-d). Non-emitting power capacity projections of power sector only, and all sector demand are shown in (e-h). Non-emitting energy shares in total energy demand of residential, industry, power, and transportation are shown in (i-l) with numbers representing the shares in 2035.

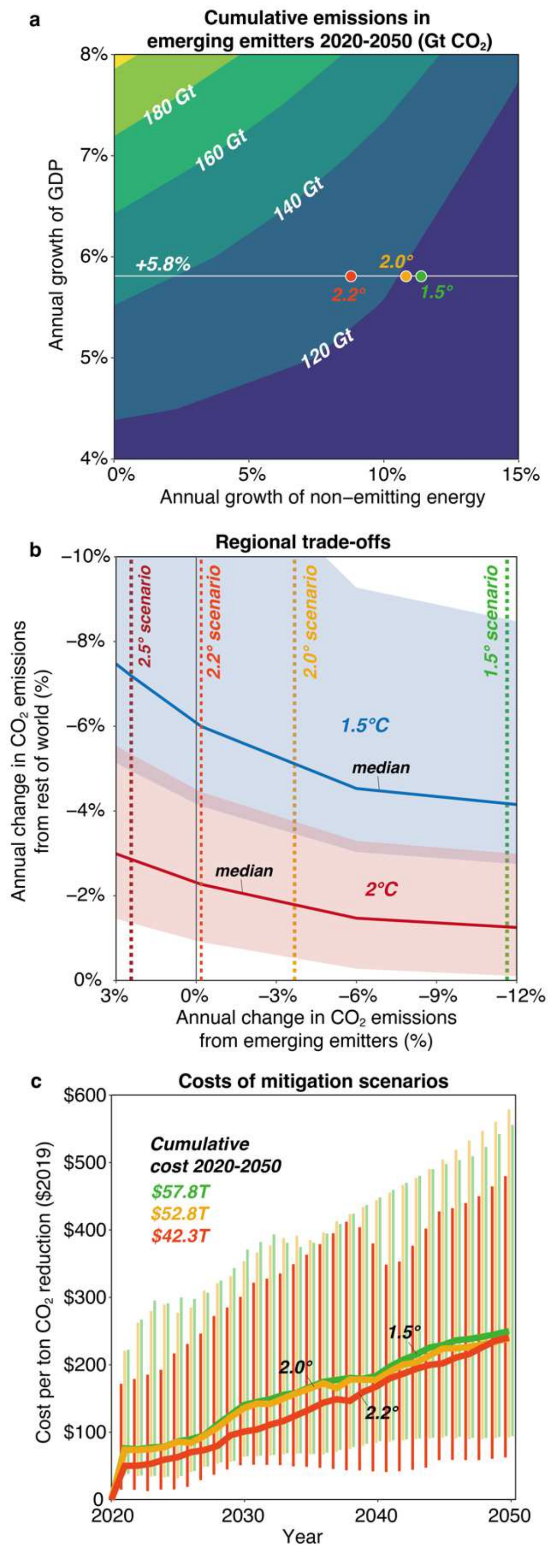

Fig. 4. Comparisons of emerging emitter scenarios and climate targets. a, Cumulative CO_2 emissions from emerging emitters 2020-2050 (contours) depend upon both energy demand of economic growth and the non-emitting energy growth. The white line shows the annual growth rate of GDP under the scenarios, and the red, orange and yellow points show the 2.2°, 2-degree and 1.5° scenarios. **b,** Annual changes in emissions from emerging emitters have important implications for the rate of emissions reductions required in the rest of the world to limit global warming below 1.5°C or 2°C. The blue line shows the combinations of the annual changes of emissions of the two types of countries to reach the 1.5 °C target, and the shadow shows the 66% confident interval for that. The red line and shadow represent the same for the 2°C target. Vertical dashed lines represent the annual growth rate of the emerging emitters under the scenarios of the 2.5°, 2.2°, 2-degree and 1.5° scenarios. **c,** Costs per ton CO_2 reduction and cumulative costs of 2.2° (red), 2-degree (orange) and 1.5° (yellow) scenarios. Error bars represent the 66% confident intervals of costs per ton CO_2 reduction of corresponding scenarios.

Supplementary Files

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