Key indicators to track current progress and future ambition of the Paris Agreement

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Current emission pledges to the Paris Agreement appear insufficient to hold the global average temperature increase to well below 2°C above pre-industrial levels[1]. Yet, details are missing on how to track progress towards the 'Paris goal', inform the five-yearly 'global stocktake', and increase the ambition of Nationally Determined Contributions (NDCs). We develop a nested structure of key indicators to track progress through time. Global emissions[2,3] track aggregated progress[1], country-level decomposition track emerging trends[4-6] that link directly to NDCs[7], and technology diffusion[8-10] indicates future reductions. We find the recent slowdown in global emissions growth[11] is due to reduced growth in coal consumption since 2011, primarily in China and secondarily the United States[12]. The slowdown is projected to continue in 2016, with global CO_2 emissions from fossil fuels and industry similar to the 2015 level of 36GtCO_2. Explosive, policy-driven growth in wind and solar has contributed to the global emissions slowdown, but has been less important than economic factors and energy efficiency. We show that many key indicators are currently broadly consistent with emission scenarios that keep temperatures well below 2°C, but the continued lack of large-scale Carbon Capture and Storage[13] threatens 2030 targets and the longer-term Paris ambition of net-zero emissions.

Tracking progress of individual countries towards a collective global climate target requires a hierarchy of indicators spanning different levels of detail and periods of time (Figure 1). At the aggregated level one could track global temperature, atmospheric concentrations, and greenhouse gas emissions[2,3]; CO_2 emissions are particularly relevant due to their dominant role in perturbing the climate system and strong connections to climate policy. We project global CO_2 emissions from fossil fuels and industry in 2016 to be 36GtCO_2 (see Methods), approximately the same as emissions in 2014 and 2015, indicating that growth in global CO_2 emissions has stalled, at least temporarily[11]. While zero global emissions growth is a positive step in addressing climate change, cumulative emissions are still rising and emissions need to rapidly decrease until they reach zero to remain consistent with the Paris Agreement[1].

More relevant for policy implementation is to track progress nationally to assess historical and future trends in emissions[4-6], progress towards emission pledges[14], and the adequacy of pledges to achieve global targets[1]. Chinese emissions grew at 10%/yr in the 2000's, but have been largely stable since 2013 potentially indicating a peak in emissions earlier than expected[12]. US emissions declined from 2007 to 2012 at over -2%/yr due to a weaker economy, a shift from coal to gas, and growth in renewables[15], but emissions have been relatively flat since 2012. EU emissions declined by -0.7%/yr from 2000-2010 and -2.2%/yr from 2011-2015, ensuring the EU is on track to meeting its 2030 emission pledge. India has had sustained emissions growth of 5-6%/yr over the last decade, and even with its NDC, it is expected that high growth rates will continue into the future[16].

It is not clear if the driving forces behind these global and country-level trends will be sustained in the future. If the observed trends are driven by strengthening of energy and climate policies, then good progress can be expected towards achievement of the NDCs, with available options for raising mitigation ambitions. If the trends are largely due to lingering economic weakness[17], or other short-term factors, then emissions growth may rebound[18]. Disentangling the factors causing short-term changes in emissions is critical, otherwise current or future policies may be inconsistent with emission pledges[1].

The implementation of the Paris Agreement requires a consistent and harmonised approach to track progress at different levels of detail and over different time periods. The Kaya Identity is one such approach[5], in which different components form an interconnected and nested structure (Figure 1, see Methods). Each component of the identity can be decomposed into measurable indicators directly impacted by energy and climate policy[5], which themselves can be further decomposed. Many countries already express their climate policies in terms of Kaya components, such as the energy intensity of Gross Domestic Product (GDP), or sub-components such as the share of non-fossil energy in total energy consumption[7].

The indicators in the top three layers of Figure 1 are the outcomes of dynamics that occur at a more detailed level (bottom two layers). The carbon intensity of fossil fuel combustion (layer 3) can be reduced by substituting coal with natural gas or by using Carbon Capture and Storage (CCS; layer 4). The share of fossil fuels in energy consumption (layer 3) can be decreased by replacing fossil fuels with renewables (layer 4). The diffusion of new technologies may require longer-term investments, research and development[19], which may be tracked[9] via private and public investments[16], price development[8] and deployment[13] (layer 5). If technological progress is more rapid than expected, it may support and drive increased ambition of country pledges.

We explore this nested structure using global and country-level data (Figure 1). We focus on the Kaya-derived indicators: CO_2 emissions (layer 1); GDP, energy intensity of GDP (e.g., energy efficiency), and CO_2 per unit energy (layer 2); and CO_2 intensity of fossil fuels and share of fossil fuels in total energy consumption (layer 3). These indicators are the most relevant for the current slowdown in CO_2 emissions growth[11], are important indicators in emission scenarios consistent with the Paris goal[20], and cover the diversity of energy-related indicators used in the NDCs. We focus on emissions from the energy system (fossil fuel use) because this represents the largest share of current and future CO_2 emissions. The drivers are different for CO_2 emissions not derived from energy consumption, such as cement (5% of global total) and land-use change (10% global total)[21].

A decomposition of the world and key countries (Figure 2 and Supplementary Figure 1) shows that growth in GDP (green) has exerted upward pressure on CO_2 emissions, in most cases only partially offset by downward pressure from improved energy intensity of GDP (purple) and lower carbon intensity of energy (orange). Country trajectories differ, but when averaging over years to decades to remove interannual variability, three factors are most prominent (Figure 2). First, GDP growth in the EU28, US, and China has been lower in the decade 2005-2015 compared to 1995-2005 (values in 2010 and 2000 in Figure 2) leading to lower emissions growth in the later period. The apparent increase in GDP growth since 2013 in the US and globally is partially due to the reduced influence of the global financial crisis in 2008/2009 from the smoothing process (see Methods, and compare Figure 2 and Supplementary Figure

1). Second, improvements in the energy intensity of GDP (Figure 2, purple) has ensured that energy consumption has grown more slowly than GDP (Supplementary Figure 2). The declines in energy intensity are an important long-term trend as economies develop, become more efficient, and shift to services[5]. Third, there are signs of emerging declines in carbon intensity of energy globally, in China and the US, and of continual declines in the EU28 (Figure 2, orange). The declining energy and carbon intensities ensure that CO_2 emissions grow at a slower rate than GDP (Figure 2, black line).

Emission scenarios consistent with the Paris Agreement (Figure 3, top) show that stringent climate policy is expected to only slightly accelerate historical improvements in energy intensity compared to baseline scenarios. In contrast, the scenarios indicate that significant mitigation is achieved by deep and sustained reductions in the carbon intensity of energy (Figure 3, bottom). Identifying signs of emerging trends in the carbon intensity of energy (Figure 2) could be an early indicator of progress in mitigation.

Due to the importance of carbon intensity of energy in emission scenarios and for emerging trends, we decompose the carbon intensity of energy (Figure 2, orange) into the share of fossil fuels in total energy consumption and carbon intensity of fossil fuel combustion (Level 3 in Figure 1; Figure 4). The trends vary by country, indicating the effectiveness of different factors. China has shown a strong decline in the share of fossil fuels in total energy consumption (orange) driven by growth in renewables, with continual improvements in the carbon emitted per unit of fossil fuel (green) due to a declining share of coal. The USA shows strong declines in carbon per unit of fossil fuel consumed (green) representing the gains from a shift from coal to natural gas, with smaller reductions from growth in renewables (orange). Our US results are consistent with an earlier study[15], but we find that, to date, coal to gas is more important in driving US emissions than the expansion of renewables[22] (Figure 4). The EU carbon intensity decline is dominated by the growing share of renewables in total energy consumption (orange), with decreasing gains from the carbon emitted from fossil fuel consumption (green). There are no clear trends in India. Globally, after a period of rapid recarbonisation[6] in the 2000's, there is an emerging trend of declining carbon intensity, primarily driven by an increased share of non-fossil energy sources.

Despite the improvements in the carbon intensity of energy, and its components (Figure 4), energy consumption remains, in most cases, the dominant driver of CO_2 emissions (Supplementary Figure 3). Although there has been strong growth in solar and wind power in recent years, the growth in global energy consumption has largely been dominated by increases in fossil fuel consumption and, to a much lesser extent, nuclear and hydro power (Supplementary Figure 4). Because of the recent decline in coal consumption in China[12], the contribution of the growth in renewables to the growth in total energy was remarkably large globally in 2015 (~50%). In the US and EU, fossil fuel consumption continually declined, and the contributions of the growth in wind and solar power to the growth in energy consumption are more significant and, in some years, dominant.

The recent gains in renewable energy consumption are significant, but it will be difficult for renewable energy to supply the entire annual growth in energy consumption in the short-term unless growth in global energy consumption declines further. If the annual growth in energy consumption remains stable, or declines further, then global CO_2 emissions are likely to remain flat or even decline in the short-term. A return to stronger GDP and energy consumption growth could lead to renewed growth in emissions through increased capacity utilisation of existing coal plants and rapid construction of new coal plants[23]. Policies that lock in the recent reductions in coal consumption and avoid new capacity additions[12], can potentially avoid a rebound in coal consumption and emissions[18].

Future changes in the carbon intensity of energy (Figure 3) are driven by the development and deployment of particular technologies (Level 4 of Figure 1). Scenarios consistent with the Paris goal require a decreasing share of fossil fuels in energy use (Figure 5a). Despite the large increases in fossil energy consumption in the last decades, current trends in fossil energy emissions are still largely consistent with most 2°C scenarios (Supplementary Figure 5). However, declines in fossil energy, particularly coal, need to be initiated soon, particularly given existing infrastructure lock-in[24].

The relatively high fossil energy consumption in many 2°C scenarios is predicated on the large-scale deployment of Carbon Capture and Storage (CCS) in nearly all emission scenarios (Figure 5b). In addition, most scenarios require strong growth in bioenergy (Figure 5d), a large share which is linked with CCS for carbon dioxide removal[25]. It is uncertain whether bioenergy can be sustainably produced at the scales required[26,27], but without the large-scale deployment of CCS most models cannot produce emission pathways consistent with the 2°C goal[20,25]. Despite its importance, deployment of CCS has continued to lag behind expectations[13]. Emission scenarios require many hundreds to thousands of CCS facilities by 2030 (Figure 5b), compared to the tens currently proposed[28]. Given the lack of focus on CCS in emission pledges[7], a globally coordinated effort is needed to accelerate progress[13], better understand the risks associated with pervasive diffusion, and address social acceptability[29].

Renewable energies are currently tracking well with the requirements of most emission scenarios consistent with 2°C (Figure 5). Despite the extraordinary growth rates of wind and solar in recent years, scenarios indicate that greatly accelerated expansion is required in the next decades. According to most scenarios there is limited scope for large-scale expansion of hydropower due to geophysical constraints. Most scenarios indicate strong growth in nuclear energy, but there is renewed uncertainty in light of the drop in public support since the Fukushima Daiichi accident in 2011. Scenario analysis indicates that renewables alone may not be sufficient to avoid 2°C due to the small remaining carbon budget and the difficulty of mitigation in some sectors[20], such as agriculture and industry.

Current trends in many indicators are broadly consistent with many of the emission scenarios that limit warming to well below 2°C (Figure 5), but this masks three critical issues. First, studies clearly show that up to 2030, current emission pledges quickly deviate from what is required to be consistent with the Paris goal[1]. Second, according to the 2°C scenarios, current trends of several key technologies (e.g., CCS) deviate substantially from long-term requirements. Third, for a given energy use, if some technologies lag considerably behind expectations[13] or requirements[20], then other technologies will need more rapid deployment and higher levels of penetration into the energy system. Of particular concern is the lack of scenarios exploring transformational lifestyle and behavioural changes, low-CCS and high renewables[30], and alternative forms of carbon dioxide removal[25,31] and solar radiation management[32].

The nested structure we have demonstrated and applied (Figure 1) facilitates the tracking of key indicators that need significant change over time to avoid 2°C of warming. The methodology allows a consistent and robust decomposition of current emission, energy, and technology trends, and thereby helps identify where future policy resources need to be placed. While tracking emissions is important, we argue that extending tracking across indicators, scales, and time periods will make it more likely that policies will be implemented that ensure the necessary societal transition consistent with the Paris Agreement.

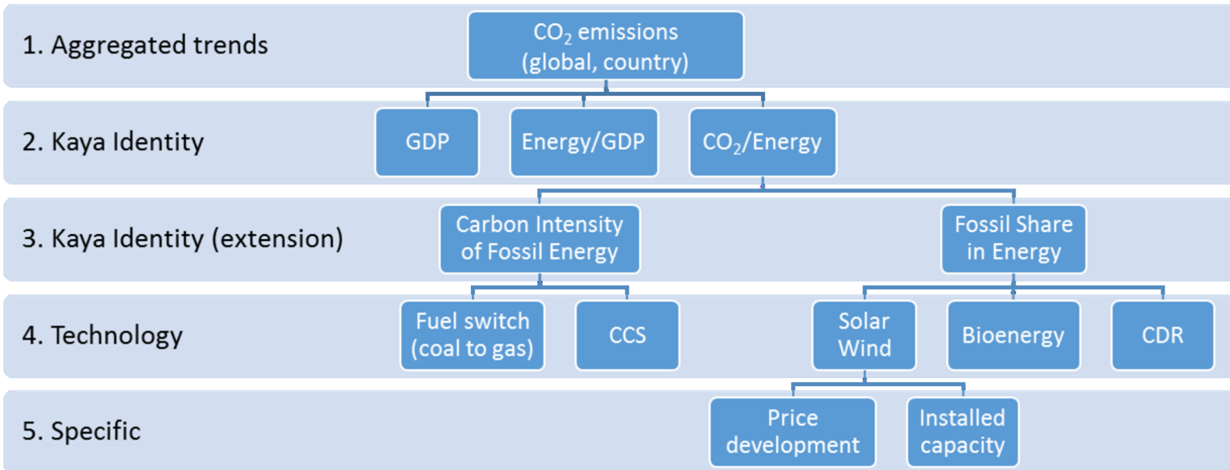

Figure 1: A schematic hierarchy of potential indicators for tracking progress of the Paris Agreement at different levels. This schematic is not exhaustive and represents a disaggregation of indicators relevant for our analysis of recent trends in emissions, with a particular focus on the carbon intensity of energy (CO_2/Energy). The upper layers are closer to the outcomes of policy, often used in emission pledges (emissions, emission intensity), while the lower layers represent more detailed technology inputs required to meet the outcomes. The structure can be analyzed over different time periods (years, decades, century). We only show CCS for fossil fuels, even though CCS apply to bioenergy and industry. Each horizontal layer represents a component of similar aggregation. GDP: Gross Domestic Product, CCS: Carbon Capture and Storage, CDR: Carbon Dioxide Removal.

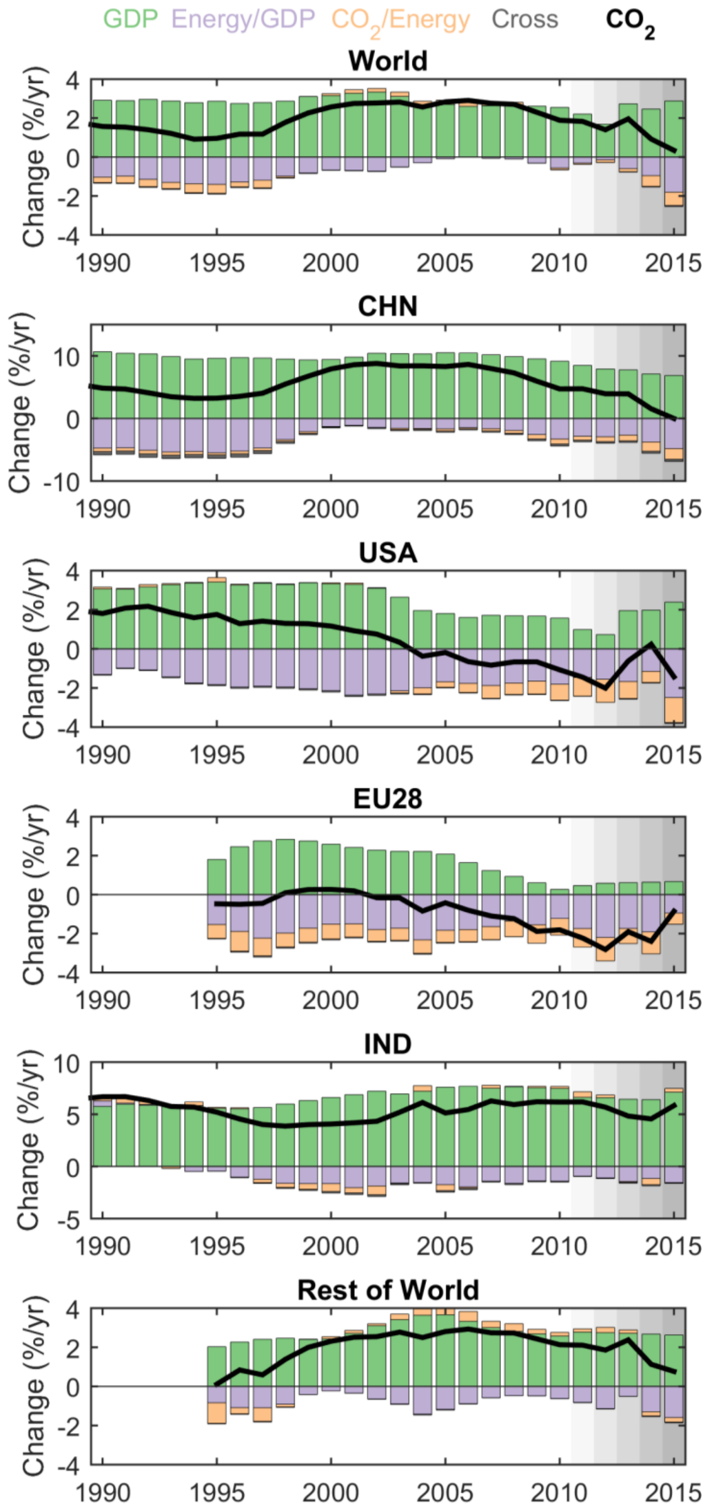

*Figure 2: A Kaya Identity decomposition of CO_2 emissions and its immediate drivers (Levels 1 & 2 in Figure 1), for the world (**a**), China (**b**), USA (**c**), EU28 (**d**), India (**e**), and the rest of the World (**f**); note varying y-axes. The data is smoothed with a 11-year window to show longer term trends, and the grey shading from 2010-2015 represents a diminishing window length as 2015 is approached. The missing data before 1995 is since there is no GDP data for the EU28 before 1990. Growth in GDP exerts upward pressure on emissions, energy efficiency (Energy/GDP) downward pressure, and in recent years, carbon intensity (CO_2/Energy) downward pressure. "Cross" is a small interaction term (see Methods). See Supplementary Figure 1 for a non-smoothed version.*

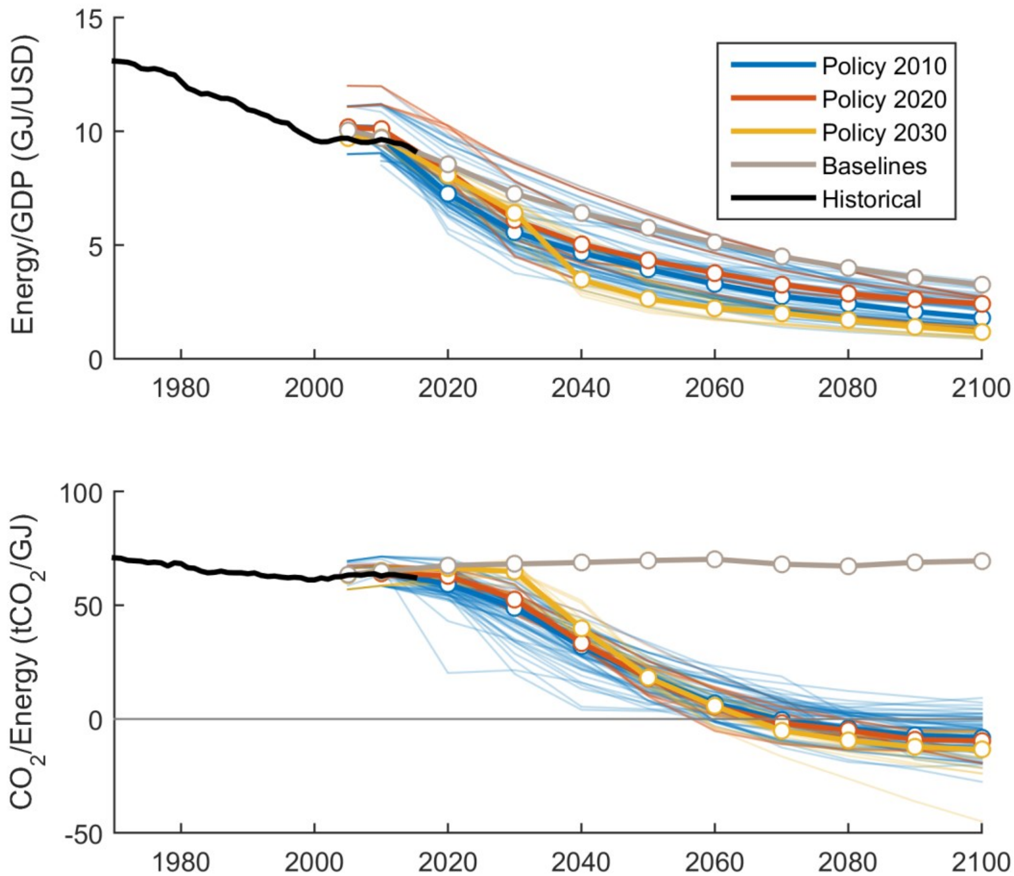

Figure 3: Energy intensity of GDP (top) and carbon intensity of energy (bottom), both shown in Level 2 of Figure 1. Data is shown for the historical period (black), the 2°C scenarios assessed in AR5[38], and the median of the associated baselines (brown). The 116 2°C scenarios are split into different categories with global climate policies starting in 2010 (blue), 2020 (red), and 2030 (orange). The light lines are individual scenarios and the dark with white markers medians. Historically and in the long-term, Energy/GDP has trended downwards and the 2°C scenarios suggest only a slight acceleration to bridge the baseline trend with the 2°C scenarios. The scenarios indicate that most future mitigation is due to reductions in CO_2/Energy, and this partly explains our focus on this term in our analysis.

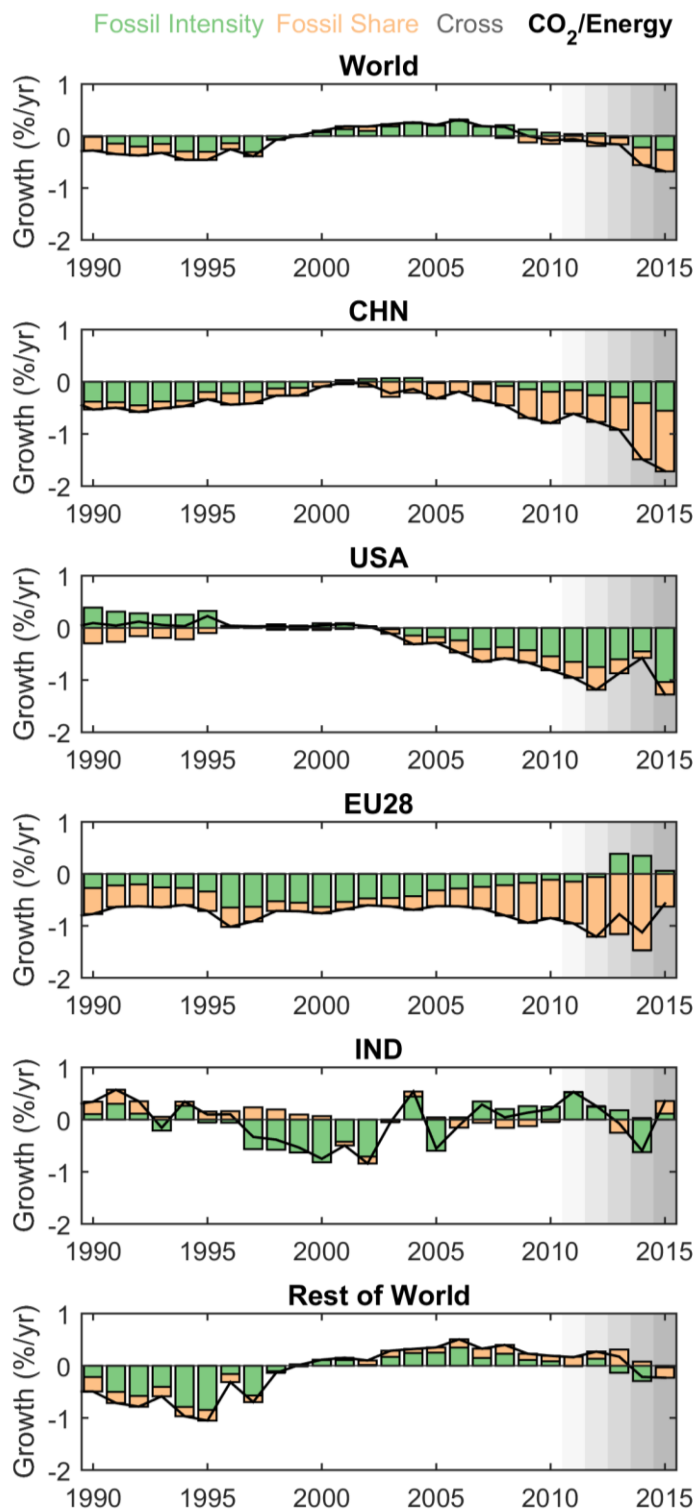

*Figure 4: A decomposition of the carbon intensity (CO_2/Energy) into the carbon intensity of fossil fuel consumption (CO_2/Fossil, called Fossil Intensity) and the share of fossil fuels in energy consumption (Fossil/Energy), Level 3 in Figure 1. Data shown are for the world (**a**), China (**b**), USA (**c**), EU28 (**d**), India (**e**), and the rest of the World (**f**). The data has been smoothed with a 11-year window to show longer term trends, and the grey shading from 2010-2015 represents a diminishing window length as 2015 is approached. The missing data for the EU before 1995 is since there is no data before 1990. "Cross" is a negligible interaction term (see Methods).*

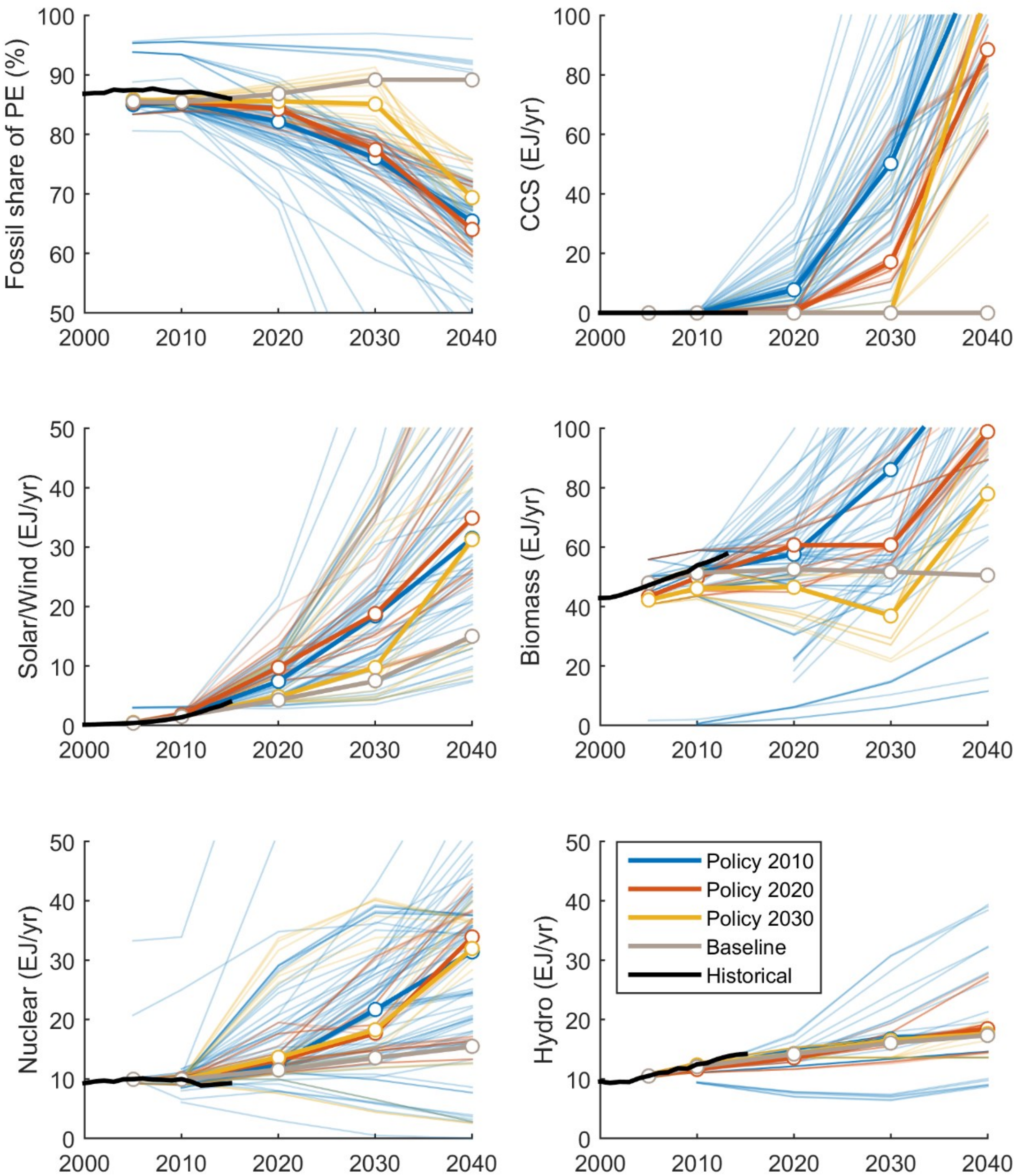

*Figure 5: Historical trends and future pathways for the fossil share of primary energy (**a**), fossil and bioenergy CCS (**b**), and renewable energy consumption disaggregated into solar and wind (**c**), biomass (**d**), nuclear (**e**), and hydropower (**f**). All panels show the historical period (black), the 2˚C scenarios assessed in AR5, and the median of the associated baselines (brown). The 116 2˚C scenarios are split into different categories with global climate policies starting in 2010 (blue), 2020 (red), and 2030 (orange). The light lines are individual scenarios and the dark with white markers medians. Current trends track well with most 2˚C scenarios, with the notable exception of CCS. If CCS does not live up to expectations, then alternative energy sources will be required to grow faster over longer periods of time. Additional energy sources and longer time periods are shown in Supplementary Figure 5.*

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Methods

Kaya Identity. We apply the Kaya Identity in our core analysis[5]

$$C = G \times \frac{E}{G} \times \frac{C}{E} = C \times I_E \times I_C$$

where *C* is CO_2 emissions from fossil-fuel combustion, *G* is the Gross Domestic Product (GDP) in constant prices, *E* is total primary energy use (fossil- and non-fossil fuels), I_E is the energy use per unit GDP (energy intensity of GDP), and I_C is the carbon emissions per unit energy use (carbon intensity of energy). We do not include population as a separate component, and instead focus on aggregated GDP. We find it is useful to further decompose the carbon intensity of energy,

$$I_C = \frac{C}{E_F} \times \frac{E_F}{E} = F_i \times F_s$$

where E_F is the primary energy consumption of fossil fuels, F_i is the carbon intensity of fossil fuel combustion and F_s is the share of fossil-fuel consumption in total energy consumption.

Decomposition. We performing Index Decomposition Analysis[33] (IDA) as we do not aim to assess structural changes. Further, we keep the number of components in each decomposition low to avoid difficulties interpreting the driver of changes[34]. A decomposition with *n* factors has *n!* unique decompositions and there are a variety of ways of dealing with non-uniqueness. We take standard forward differences and keep the interaction terms separate. As an example of a two factor decomposition, $f=xy$,

$$\Delta f(t) = y(t)\Delta x + x(t)\Delta y + \Delta x \Delta y$$

where $\Delta x(t)=x(t+\Delta t)-x(t)$. The strength of this approach is that in relative terms

$$\frac{\Delta f}{f(t)} = \frac{\Delta x}{x(t)} + \frac{\Delta y}{y(t)} + \left(\frac{\Delta x}{x(t)}\frac{\Delta y}{y(t)}\right)$$

each term is the standard annual growth rate (in percent) of each factor and the magnitude of the interaction term can be isolated. For example, for each year in Figure 2 the growth rate of CO_2 emissions is the sum of the growth rates of GDP, energy intensity, and carbon intensity, with a small interaction term (labelled ‘cross’).

Data. As explained in the main text, we focus on CO_2 emissions from fossil fuels only. The CO_2 emissions data[3] is from the Carbon Dioxide Information Analysis Center[35] (CDIAC) up to 2013 with 2014 and 2015 projected by fuel-type based on the BP Statistical Review of World Energy[36], but for developed countries we overwrite this data from 1990 to 2014 using official reports to the UNFCCC. The CDIAC emissions data did not include the full revisions to Chinese data[37], so we followed the BP methodology[36] to estimate the emissions by fuel type (to be consistent with CDIAC). The difference between Chinese estimates of CDIAC and BP were propagated through to the global total to ensure consistency. Energy data is taken from BP, which scales up all non-fossil energy sources by a factor 0.38 to account for different efficiencies of fossil and non-fossil fuels in producing final energy[38]. Further, BP only reports commercial biomass and we include traditional biomass from the International Energy Agency (IEA). GDP is taken from UN and is measured in constant 2005 prices[39]. Our analysis faces important data challenges, but these should not affect our findings unduly. First, most developed countries officially report emission statistics (Annex I countries to the UNFCCC), though this will change as the Paris Agreement is implemented[40]. This limitation means that we have to source emission data for developing countries (non-Annex I countries) from non-official sources[3]. Second, economic and energy consumption data consistent with the reported emissions are rarely reported. Even though energy, economic, and emission statistics are ultimately all derived from official national data, third-party data suppliers and national governments may apply different assumptions, limiting the ability for reliably tracking of some NDCs. These challenges mean that we need to ensure our findings are not due to inconsistencies between different datasets. These issues have implications far beyond our analysis, and highlight the need for harmonised official reporting of economic, energy, and emission statistics.

Projections. To estimate emissions in 2016 we separate out China, the US, and treat the rest of the world separately[3]. For China, we use monthly data from a variety of Chinese sources to estimate full year emissions[3]. For the US, we use estimates of fossil-fuel emissions from the US Energy Information Administration[41], and supplement with estimates of cement consumption[3]. For the remaining countries, we add the 10-year average growth in CO_2/GDP to GDP growth projections from the International Monetary Fund[3]. As emphasised elsewhere[3], the 2016 estimates have additional uncertainties and the estimates should not be over interpreted. Most uncertainty lies in interpreting the uncertainties[37] and future trends[12] of Chinese emissions.

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