LETTERS
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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 decompositions 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 use since 2011, primarily in China and secondarily in 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 36 $GtCO_2$. Explosive and 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 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 time periods (Fig. 1). At the aggregate level one could track global temperature, atmospheric concentrations, and greenhouse gas (GHG) emissions[2,3]; CO_2 emissions are particularly relevant due to their dominant role in climate policy and long-lasting effect in perturbing the climate system. Global CO_2 emissions from fossil fuels and industry are projected[3] to be 36.4 $GtCO_2$ in 2016, approximately the same as in 2014 and 2015, indicating that growth in global CO_2 emissions has stalled for the third year in a row[11]. Although this is a positive step towards 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^{-1} in the 2000s, 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^{-1} 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^{-1} from 2000 to 2010 and −2.2% yr^{-1} from 2011 to 2015, ensuring the EU is on track to meeting its 2030 emission pledge. India has sustained emissions growth of 5–6% yr^{-1} over the past decade and, even with its NDC, is expected to have high future growth rates[16].

It is not clear if the driving forces behind these global and country-level trends will be sustained. If the observed trends are driven by strengthening of energy and climate policies, then good progress can be expected towards achieving the NDCs, with flexibility to raise 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 therefore critical, otherwise current or future policies may be inconsistent with emission pledges[1].

The implementation of the Paris Agreement requires a consistent and harmonized 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 (Fig. 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 use[7].

The indicators in the top three layers of Fig. 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 with Carbon Capture and Storage (CCS; layer 4). The share of fossil fuels in energy use (layer 3) can be decreased by replacing fossil fuels with renewables (layer 4). The diffusion of new technologies may require longer-term investments[19], which may be tracked[9] via private and public investments[16], price declines[8], and deployment[13] (layer 5). More rapid technological progress would support and drive increased ambition of country pledges.

We explore this nested structure using global and country-level data (Fig. 1). We focus on the Kaya-derived indicators: CO_2 emissions (layer 1); GDP, energy intensity of GDP (for example, energy efficiency), and CO_2 per energy unit (layer 2); and CO_2 intensity of fossil fuels and share of fossil fuels in total energy use (layer 3). These indicators are the most relevant for the current slowdown in CO_2 emissions growth[11], are important indicators in

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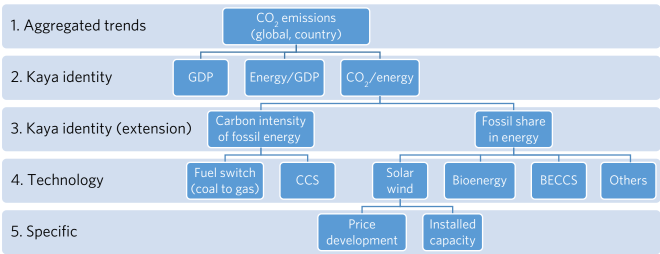

Figure 1 | A schematic hierarchy of potential indicators for tracking progress of the Paris Agreement at different levels. This schematic is not unique or exhaustive, and represents a disaggregation of indicators relevant for our analysis of recent trends in emissions, with a focus on the carbon intensity of energy (CO_2/energy). The upper layers are closer to the outcomes of policy, often used in emission pledges (emissions, emission intensity), whereas the lower layers represent more detailed technology inputs required to meet the outcomes. The structure can be analysed over different time periods (years, decades). Each layer represents components of similar aggregation. GDP, Gross Domestic Product; CCS, Carbon Capture and Storage; BECCS, Bioenergy with CCS; Others, nuclear, hydro, and other forms of renewable energy.

low-emission scenarios[20], and cover energy-related indicators used in the NDCs. We focus on CO_2 emissions from the energy system, representing 70% of global GHG emissions in 2010[5]. The drivers are different[5] for non-CO_2 GHGs, such as agriculture, and CO_2 emissions not derived from energy use, such as cement (5%) and land-use change (10% total CO_2 emissions).

A decomposition of the world and key countries (Fig. 2 and Supplementary Fig. 1) shows that, over long periods, 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 developments are particularly relevant for changes in emission trajectories (Fig. 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 Fig. 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 Fig. 2 and Supplementary Fig. 1). Second, improvements in the energy intensity of GDP (Fig. 2, purple) have ensured that energy use has grown more slowly than GDP (Supplementary Fig. 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 (Fig. 2, orange). The declining energy and carbon intensities ensure that CO_2 emissions grow at a slower rate than GDP (Fig. 2, black line).

Emission scenarios consistent with the Paris Agreement (Fig. 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 (Fig. 3, bottom). Identifying signs of emerging downward trends in the carbon intensity of energy (Fig. 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 (Fig. 2, orange) into the share of fossil fuels in total energy use and carbon intensity of fossil-fuel combustion (Level 3 in Fig. 1; Fig. 4). The trends vary by country[21], indicating the

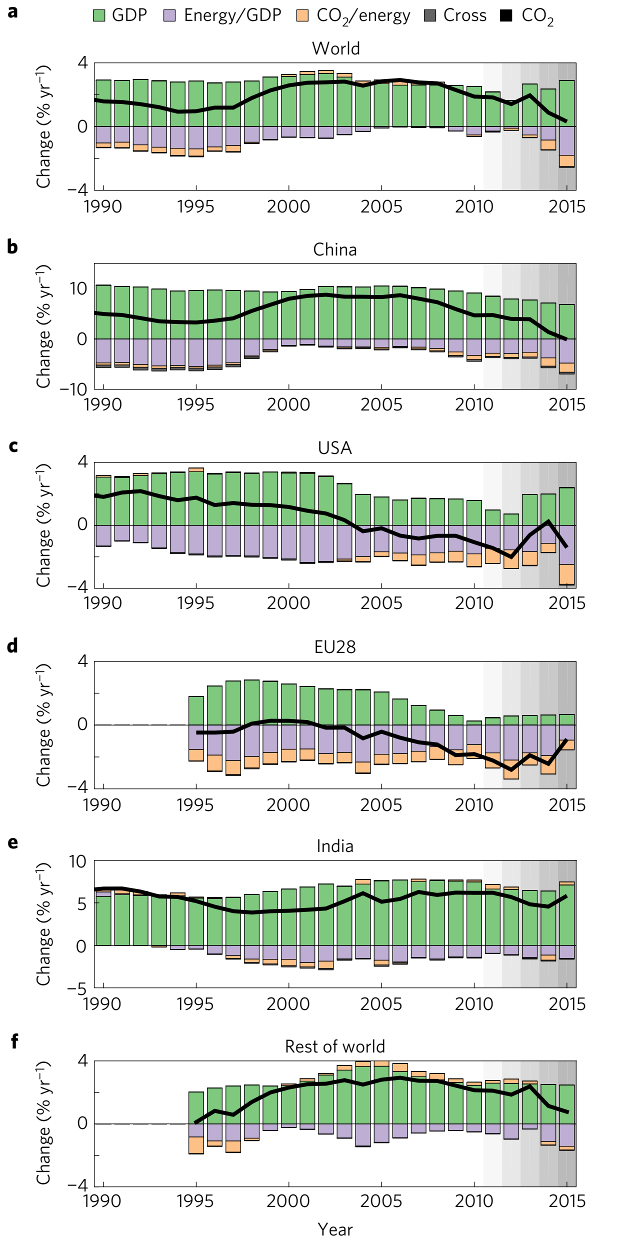

Figure 2 | A Kaya Identity decomposition of CO_2 emissions and their immediate drivers (Levels 1 and 2 in Fig. 1). Data are shown for the world (**a**), China (**b**), USA (**c**), EU28 (**d**), India (**e**), and the rest of the World (**f**); note varying *y*-axes. The data is smoothed with a 11-year 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 because there is no GDP data for the EU28 before 1990. Growth in GDP exerts upward pressure on emissions, energy efficiency (energy/GDP) exerts downward pressure, and in recent years, carbon intensity (CO_2/energy) exerts downward pressure. 'Cross' is a negligible interaction term (see Methods). See Supplementary Fig. 1 for a non-smoothed version.

effectiveness of different factors. China has shown a decline in the share of fossil fuels in total energy use (orange) driven by renewables growth, with continual improvements in the carbon emitted per unit of fossil fuel (green) due to a declining coal share. The US shows 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). Results for the US are consistent with an earlier study[15], but we find that

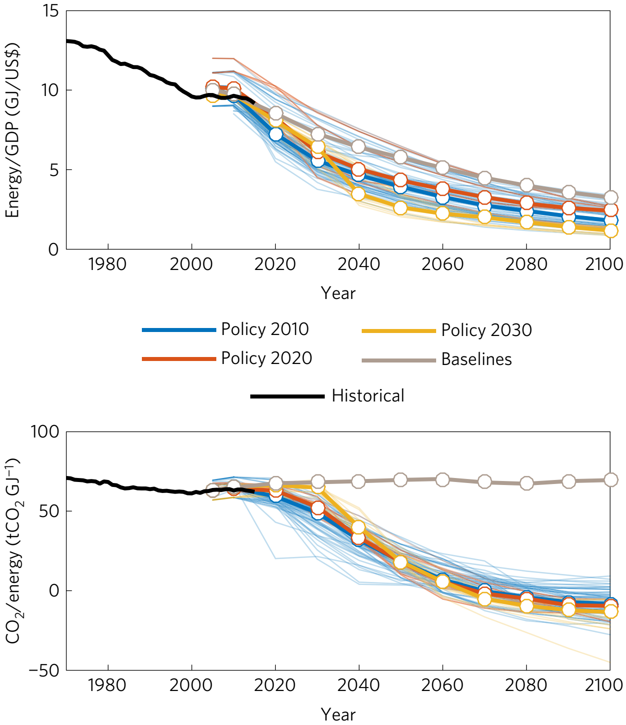

Figure 3 | Energy intensity of GDP (top) and carbon intensity of energy (bottom), both shown in Level 2 of Fig. 1. Data is shown for the historical period (black), the 2 °C scenarios assessed in AR5 (ref. 34), and the median of the associated baselines (brown). The 116 2 °C scenarios are split into different categories with global climate policies starting in 2010 (blue), 2020 (red), and 2030 (orange). The light lines are individual scenarios and the dark lines with white markers are medians. Historically, and in the long term, energy/GDP has trended downwards and the 2 °C scenarios suggest only a slightly higher energy intensity of GDP improvement compared to the baselines. 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.

substituting coal with gas is more important than the expansion of renewables[22] (Fig. 4). The EU carbon intensity decline is dominated by the growing share of renewables in total energy use (orange), with decreasing gains from the carbon emitted from fossil-fuel use (green). There are no clear trends in India. Globally, after a period of rapid recarbonization[6] in the 2000s, there appears to be an emerging trend of declining carbon intensity, primarily driven by an increased share of non-fossil energy sources, consistent with requirements of 2 °C scenarios (Fig. 3, bottom).

Despite the improvements in the carbon intensity of energy, and its components (Fig. 4), energy use remains the dominant driver of CO_2 emissions (Supplementary Fig. 3). Although there has been strong growth in solar and wind power recently, the growth in global energy use has largely been dominated by increases in fossil-fuel use and, to a lesser extent, nuclear and hydropower (Supplementary Fig. 4). Because of the recent decline in Chinese coal use[12], the contribution of renewables growth to total energy growth was remarkably large globally in 2015 (∼50%). In recent years, the use of fossil fuels in the US and EU declined, and the relative contributions of the growth in wind and solar power are significant and, in some years, dominant.

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

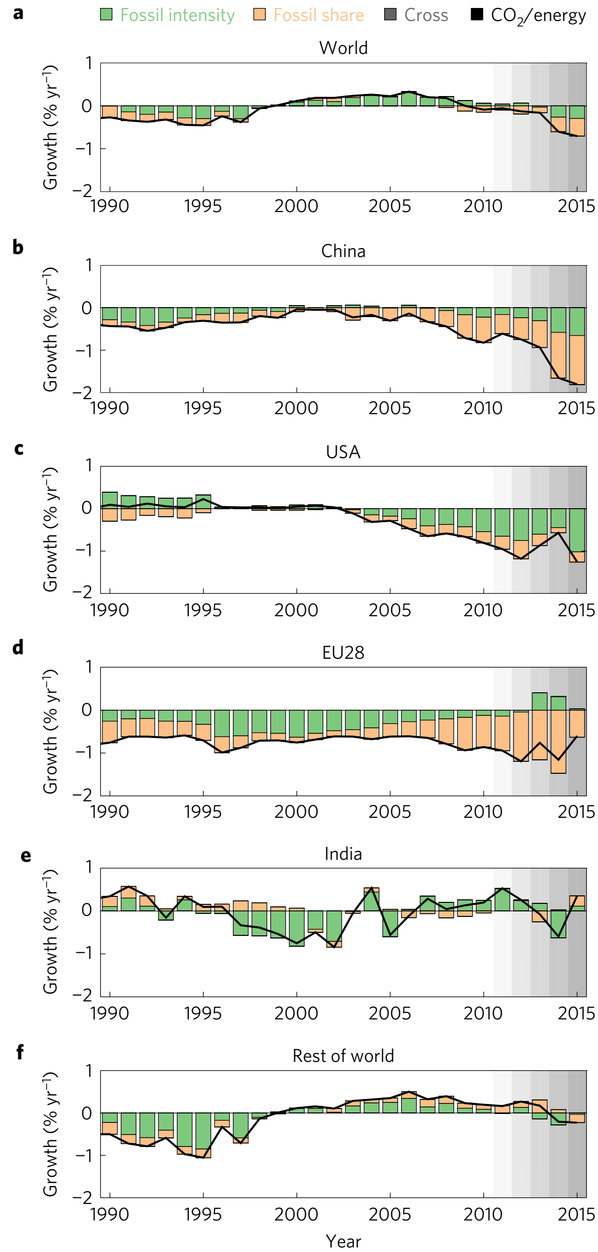

Figure 4 | A decomposition of the carbon intensity (CO_2/energy) into the carbon intensity of fossil-fuel use (CO_2/fossil, called fossil intensity) and the share of fossil fuels in energy use (fossil/energy), Level 3 in Fig. 1. Data shown are for the world (**a**), China (**b**), USA (**c**), EU28 (**d**), 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 because there is no data before 1990. 'Cross' is a negligible interaction term (see Methods).

Future changes in the carbon intensity of energy (Fig. 3) will be driven by the development and deployment of alternative technologies (Level 4, Fig. 1). Scenarios consistent with the Paris goal require a decreasing fossil-fuel share in energy use (Fig. 5a). Despite

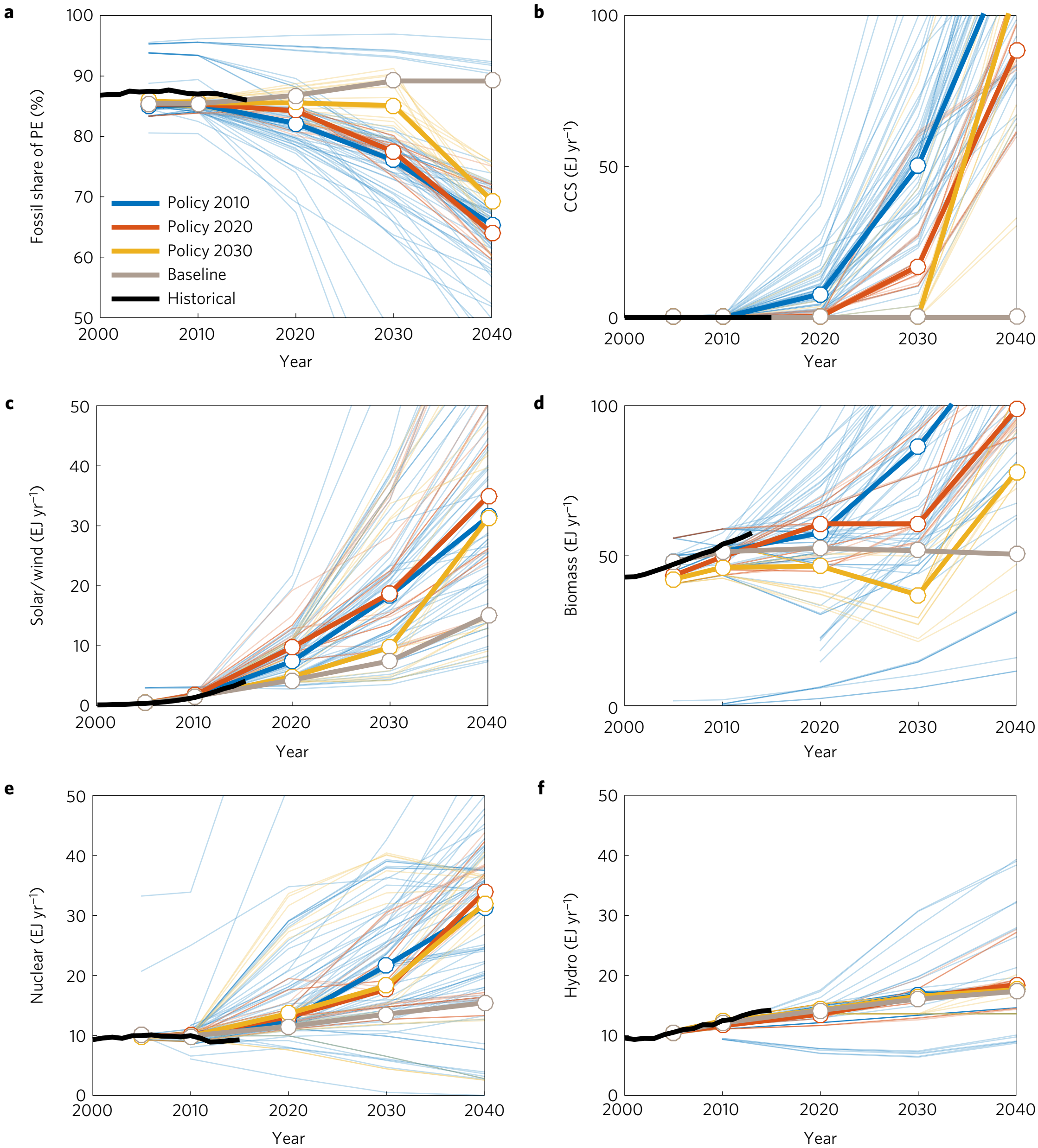

Figure 5 | Historical trends and future pathways to 2040. Data are shown for the fossil share of primary energy (**a**), fossil and bioenergy CCS (**b**), and renewable energy use disaggregated into solar and wind (**c**), biomass (**d**), nuclear (**e**), and hydropower (**f**). All panels show the 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 lines with white markers are medians. Current trends appear to 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 Fig. 5, and Supplementary Fig. 6 shows CCS (as in **b**, but extended to 2100) in energy units (EJ yr^{-1}) and the amount of CO_2 captured ($GtCO_2$ yr^{-1}).

the large increase in fossil energy use in the past decades, current fossil energy trends remain consistent with many 2 °C scenarios (Supplementary Fig. 5). For this consistency to continue, declines in fossil energy, particularly coal, need to be initiated soon, particularly given existing infrastructure lock-in[24].

The relatively high fossil energy use in many 2 °C scenarios is predicated on large-scale deployment of CCS (ref. 25) (Fig. 5b). In addition, most scenarios require strong growth in bioenergy (Fig. 5d), a large share of which is linked with CCS for carbon dioxide removal[25,26]. It is uncertain whether bioenergy can be sustainably produced and made carbon-neutral at the scales required[27,28]. Compounding this, without large-scale CCS deployment, most models cannot produce emission pathways consistent with the 2 °C goal[20,26]. Despite its importance, CCS deployment has continued to lag behind expectations[13]. Emission scenarios require a rapid ramp-up of CCS facilities, potentially 4000 facilities by 2030 (Fig. 5b and Supplementary Fig. 6), compared to the tens currently proposed by 2020[29]. Given the lack of focus on CCS in emission pledges[7], a globally coordinated effort is needed to accelerate progress[13], better understand the technological risks[25], and address social acceptability[30].

Renewable energies are currently tracking well with the requirements of most 2 °C emission scenarios (Fig. 5). Despite the extraordinary growth rates of wind and solar in recent years, greatly accelerated expansion is required in the next decades. Most scenarios have limited scope for large-scale hydropower expansion due to geophysical constraints. Further, most scenarios indicate strong growth in nuclear energy, but there is renewed uncertainty from the drop in public support since the 2011 Fukushima Daiichi accident. Scenarios indicate that renewables alone may not be sufficient to stay below 2 °C given physical constraints to large-scale deployment and the need to offset emissions in some sectors[20], such as agriculture.

Current trends in many indicators appear broadly consistent with many of the emission scenarios that limit warming to well below 2 °C (Fig. 5), but this masks four 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, current trends of some key technologies (for example, CCS) deviate substantially from long-term requirements to meet the Paris goal. Third, if some technologies lag considerably behind expectations[13] or requirements[20], then other technologies will need more rapid deployment and higher penetration levels into energy systems, a particularly important constraint for carbon dioxide removal[25]. Fourth, there is the lack of scenarios exploring opportunities and challenges of transformational lifestyle and behavioural changes, low CCS and high renewables[31], alternative forms of carbon dioxide removal[26,32] and solar radiation management[33].

The nested structure we have demonstrated and applied (Fig. 1) facilitates the tracking of key indicators that need significant change to avoid 2 °C of warming. The methodology allows consistent and robust decomposition of current emissions, energy, and technology trends, and helps identifying key policy needs. We argue that extending tracking across indicators, scales, and time periods will increase the likelihood that policies will be implemented that ensure the societal transition consistent with the Paris Agreement.

Methods

Methods, including statements of data availability and any associated accession codes and references, are available in the online version of this paper.

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Author contributions

G.P.P., J.G.C. and C.L.Q. designed the research; G.P.P. and R.M.A. performed the analysis; all analysed the results; all wrote the paper.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to G.P.P.

Competing financial interests

The authors declare no competing financial interests.

Methods

Hierarchical framework. The framework is not unique and different indicators can be used depending on the focus. We have chosen to focus on primary energy, although final energy could be used to incorporate efficiency losses in energy conversion and end-use efficiency. We have included fossil CCS in the carbon intensity indicator, as electricity is still produced from fossil fuels, but with lower emissions. We have not included carbon dioxide removal (for example, afforestation, direct air capture) unless it leads to energy production (for example, BECCS).

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

$$C = G \times \frac{E}{G} \times \frac{C}{E} = G \times I_{E} \times I_{C}$$

where C is CO_2 emissions from fossil-fuel use, 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 fossil primary energy use, F_i is the carbon intensity of fossil-fuel use and F_s is the share of fossil-fuel use in total energy use.

Decomposition. We performing Index Decomposition Analysis[35] (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[36]. 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 to assess its implications[36]. For example, for each year in Fig. 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'). Our approach is most relevant for historical, and short- to medium-term trends. If emissions cross zero, then the method may need to be revised.

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[37] (CDIAC) up to 2013, with 2014 and 2015 projected by fuel type based on the BP Statistical Review of World Energy[38]; 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[39], so we followed the BP methodology[38] 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[34]. Further, BP reports only commercial bioenergy, whereas we include traditional bioenergy from the International Energy Agency (IEA) to be consistent with the IPCC. We do note, however, that traditional[40] and future[25,26] bioenergy may not be sustainable or fully carbon-neutral. GDP is taken from the UN and is measured in constant 2005 prices[41].

Data challenges. 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[42]. 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 use 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 to reliably track some NDCs. These challenges mean that we need to ensure our findings are not due to inconsistencies between different data sets. These issues have implications far beyond our analysis, and highlight the need for harmonized 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[43], and supplement with estimates of cement[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 emphasized elsewhere[3], the 2016 estimates have additional uncertainties, and the estimates should not be over-interpreted.

Data availability. The CO_2 emissions data are available from the Global Carbon Budget 2016 v1.0 available at http://dx.doi.org/10.3334/CDIAC/GCP_2016. All energy data except for bioenergy are taken from the 2016 edition of the BP 'Statistical Review of World Energy' available at http://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy/co2-emissions.html. Bioenergy data (used only in Fig. 5d) are from the International Energy Agency's 'World Energy Balances', available at http://data.iea.org/payment/products/103-world-energy-statistics-and-balances-2016-edition.aspx. GDP to 2014 is taken from the 2015 edition of the UN Statistics Divisions data set 'GDP and its breakdown at constant 2005 prices in US Dollars' available at http://unstats.un.org/unsd/snaama/dnlList.asp. GDP for 2015 is from the International Monetary Fund's April 2016 World Economic Outlook available at http://www.imf.org/external/pubs/ft/weo/2016/01/index.htm. The AR5 scenario database is available at https://tntcat.iiasa.ac.at/AR5DB. The data are also available from the corresponding author upon reasonable request.

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