https://doi.org/10.1038/s41586-019-1364-3

Committed emissions from existing energy infrastructure jeopardize 1.5 °C climate target

Dan Tong[1,2], Qiang Zhang[2]*, Yixuan Zheng[2,3], Ken Caldeira[3], Christine Shearer[4], Chaopeng Hong[1], Yue Qin[1] & Steven J. Davis[1,2,5]*

Net anthropogenic emissions of carbon dioxide (CO_2) must approach zero by mid-century (2050) in order to stabilize the global mean temperature at the level targeted by international efforts[1–5]. Yet continued expansion of fossil-fuel-burning energy infrastructure implies already 'committed' future CO_2 emissions[6–13]. Here we use detailed datasets of existing fossil-fuel energy infrastructure in 2018 to estimate regional and sectoral patterns of committed CO_2 emissions, the sensitivity of such emissions to assumed operating lifetimes and schedules, and the economic value of the associated infrastructure. We estimate that, if operated as historically, existing infrastructure will cumulatively emit about 658 gigatonnes of CO_2 (with a range of 226 to 1,479 gigatonnes CO_2, depending on the lifetimes and utilization rates assumed). More than half of these emissions are predicted to come from the electricity sector; infrastructure in China, the USA and the 28 member states of the European Union represents approximately 41 per cent, 9 per cent and 7 per cent of the total, respectively. If built, proposed power plants (planned, permitted or under construction) would emit roughly an extra 188 (range 37–427) gigatonnes CO_2. Committed emissions from existing and proposed energy infrastructure (about 846 gigatonnes CO_2) thus represent more than the entire carbon budget that remains if mean warming is to be limited to 1.5 degrees Celsius (°C) with a probability of 66 to 50 per cent (420–580 gigatonnes CO_2)[5], and perhaps two-thirds of the remaining carbon budget if mean warming is to be limited to less than 2 °C (1,170–1,500 gigatonnes CO_2)[5]. The remaining carbon budget estimates are varied and nuanced[14,15], and depend on the climate target and the availability of large-scale negative emissions[16]. Nevertheless, our estimates suggest that little or no new CO_2-emitting infrastructure can be commissioned, and that existing infrastructure may need to be retired early (or be retrofitted with carbon capture and storage technology) in order to meet the Paris Agreement climate goals[17]. Given the asset value per tonne of committed emissions, we suggest that the most cost-effective premature infrastructure retirements will be in the electricity and industry sectors, if non-emitting alternatives are available and affordable[4,18].

International efforts to limit the increase in global mean temperature to well below 2 °C, and to 'pursue efforts' to avoid a 1.5 °C increase, entail a transition to energy systems with net-zero emissions by mid-century[1–5]. Yet recent decades have witnessed an unprecedented expansion of historically long-lived, fossil-fuel-based energy infrastructure—particularly associated with the rapid economic development and industrialization of emerging markets such as China and India[9,10]—and a shift towards natural-gas-fired power plants in the USA. Although

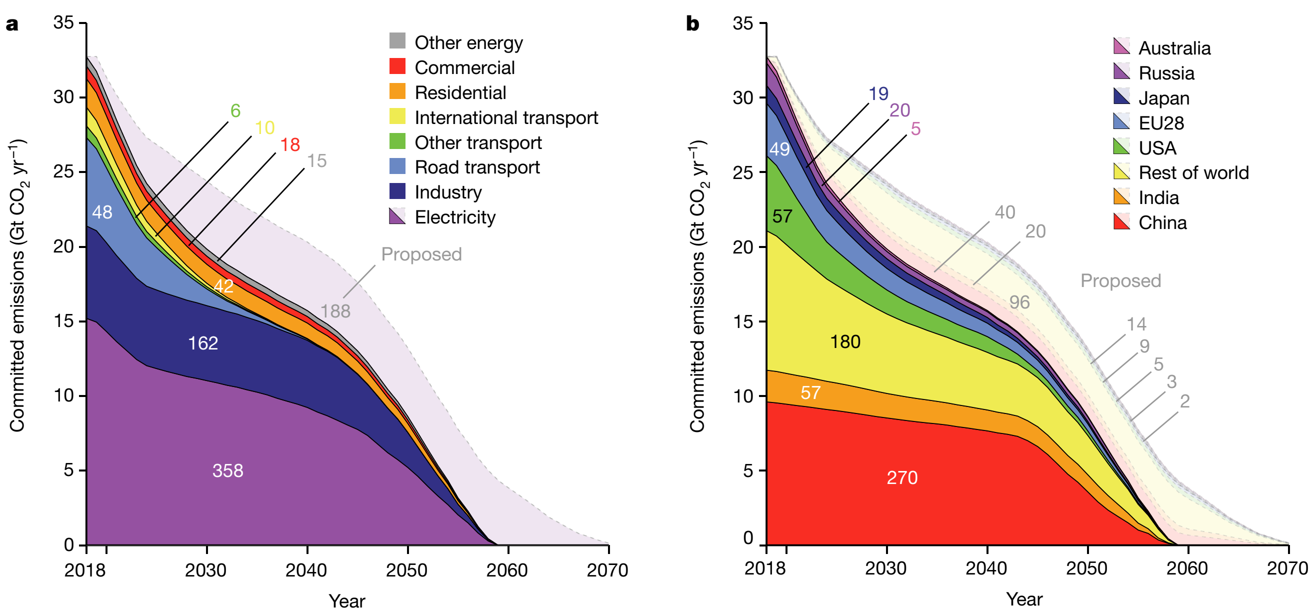

Fig. 1 | Committed annual CO_2 emissions from existing and proposed energy infrastructure. a, b, Estimates of future CO_2 emissions by industry sector (**a**; see also Supplementary Tables 1, 2) and country/region (**b**), assuming historical lifetimes and utilization rates. Emissions from existing infrastructure are shown with darker shading, and emissions from proposed power plants (that is, electricity) are more lightly shaded. Numbers within graphs show total amounts of emissions over the period shown.

[1]Department of Earth System Science, University of California, Irvine, CA, USA. [2]Ministry of Education, Key Laboratory for Earth System Modeling, Department of Earth System Science, Tsinghua University, Beijing, China. [3]Department of Global Ecology, Carnegie Institution for Science, Stanford, CA, USA. [4]Global Energy Monitor, San Francisco, CA, USA. [5]Department of Civil and Environmental Engineering, University of California, Irvine, CA, USA. *e-mail: qiangzhang@tsinghua.edu.cn; sjdavis@uci.edu

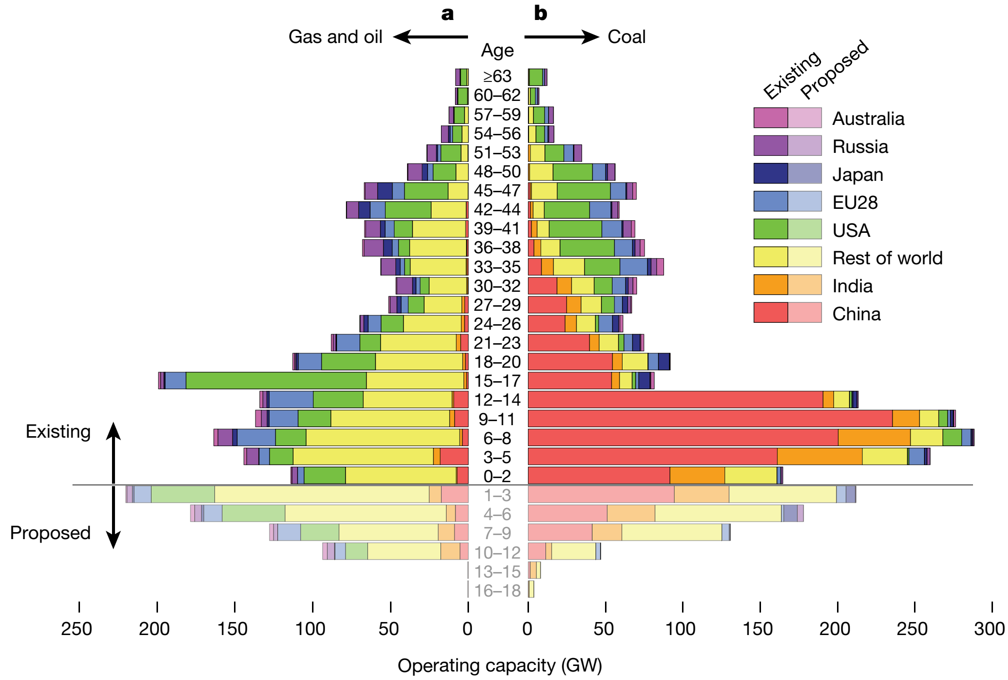

Fig. 2 | Age structure of global electricity-generating capacity. a, b, The operating capacity of gas- and oil-fired electricity-generating power units (**a**) and coal-fired units (**b**). The youngest existing units are shown at the bottom of the 'existing' section. The more lightly shaded bars underneath show proposed electricity-generating units according to the year (from now) that they are expected to be commissioned. The recent trends in Chinese and Indian coal-fired units (red and orange at the lower right) and US gas-fired units (green at the left) are easily apparent. '0 years old' means that the power units began operating in 2018.

such expansion may be slowing[19,20], substantial new electricity-generating capacity is proposed—and in many cases is already under construction[12]. Consequently, there is a tension between dwindling carbon-emissions budgets and future CO_2 emissions that are locked-in or 'committed' by existing and proposed energy infrastructure[6,21,22].

A 2010 study estimated that operating fossil-fuel energy infrastructure would emit roughly 500 Gt CO_2 over its lifetime[8]. Subsequent studies estimated that existing power plants alone committed around 300 Gt CO_2 as of 2012 (ref. [9]) and 2016 (ref. [12]), and that existing and proposed coal-fired power plants represented 340 Gt CO_2 as of 2016 (ref. [11]; Extended Data Table 1). Other studies have used integrated assessment models (IAMs) to assess the economic costs of 'unlocking' emissions under stringent climate goals[23,24], and to identify 'points of no return' past which no new infrastructure can be built without exceeding the 2 °C target[25]. Most recently, the potential climate responses to committed emissions were explored[13], using a reduced-complexity climate model and an idealized phase-out of fossil infrastructure to argue that aggressive mitigation of non-CO_2 forcing could yet limit global warming to 1.5 °C. However, it has been nearly a decade since a comprehensive bottom-up assessment of fossil infrastructure and committed emissions was made, during which years China's economy has grown tremendously, there has been a global financial crisis and a natural gas boom in the USA, and the Paris Agreement was ratified and entered into force. Substantial new fossil-fuel energy infrastructure has been commissioned over this period, proposals of new power plants have waxed and waned, and climate-mitigation efforts have grown more ambitious in many countries.

Here we present region- and sector-specific estimates of future CO_2 emissions related to fossil-fuel-burning infrastructure existing and power plants proposed as of the end of 2018, as well as the sensitivity of such estimates to assumed lifetime and utilization rates, and the economic value of associated energy assets. Our analyses are based upon a compilation of the most detailed and up-to-date datasets for energy infrastructure available (see Methods). Our central estimates assume historical lifetimes (for example, 40 years for power plants and industrial boilers and 15 years for light-duty vehicles) and utilization rates (for example, region- and fuel-specific power-plant capacity factors and region-specific averages of vehicle fuel economy and annual kilometres travelled).

Figure 1 shows future CO_2 emissions from existing and proposed energy and transportation infrastructure by sector (Fig. 1a) and country/region (Fig. 1b). We estimate that cumulative emissions by existing infrastructure, if operated as historically, will be 658 Gt CO_2. Of this total commitment, 54% or 358 Gt CO_2 is anticipated to come from existing electricity infrastructure (mainly power plants), reflecting the large share of annual emissions from electricity infrastructure (46% in 2018) and the long historical lifetimes of the infrastructure. Another 25% of the total, or 162 Gt CO_2, is related to industrial infrastructure, and 10% or 64 Gt CO_2 is related to the transportation sector (mainly on-road vehicles; Fig. 1a). This difference reveals the effect of infrastructure lifetimes: although industry and road-transportation sectors have similar annual CO_2 emissions (6.2 Gt and 5.9 Gt CO_2, respectively, in 2018), vehicle lifetimes are roughly a third as long as that of industrial capital. Finally, existing residential and commercial infrastructure represents respectively 42 Gt and 18 Gt CO_2 of committed emissions.

Global committed emissions are now at the apex of a 20-year trend. From 2002 to 2014, as China emerged as a global economic power, total committed emissions grew at an average annual rate of 9% per year (Extended Data Fig. 1a). Meanwhile, committed emissions related to infrastructure in the USA and the 28 member states of the European Union (EU28) have been shrinking since 2006 (Extended Data Fig. 1c). Since 2014, the rate of infrastructure expansion in China and India has also fallen, and committed emissions in China declined by 7% between 2014 and 2018, even as committed emissions in the rest of the world have continued to climb (Extended Data Fig. 1a, c). These most recent trends may reflect nascent shifts in China's economic structure[19] and global trade[20], and may be important harbingers of future changes in regional annual CO_2 emissions[9].

Figure 2 shows the age distribution of electricity-generating units worldwide. Overall, the youth of fossil-based generating units worldwide is striking: worldwide, 49% of the capacity now in operation was

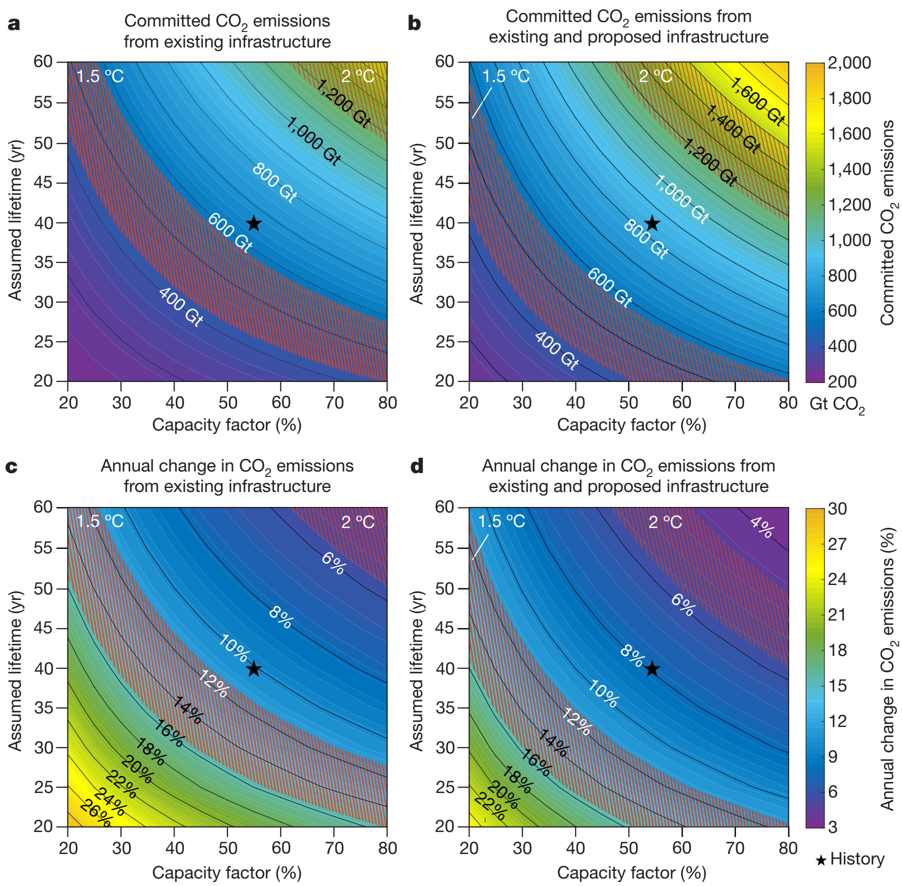

Fig. 3 | Sensitivity of committed emissions and mitigation rates to utilization rates and assumed lifetimes. a, **b**, Committed CO_2 emissions. Contours show estimates of committed CO_2 emissions related to existing infrastructure (**a**) and existing infrastructure plus proposed power plants (**b**) when the assumed lifetimes and utilization rates of electricity and industry infrastructure are varied from 20 years to 60 years (vertical axes) and from 20% to 80% (horizontal axes). **c**, **d**, Committed mitigation rates. For the same ranges of lifetime and utilization as in panels **a**, **b**, the annual rates of emission reduction span from 3% to 30% (**c**, **d**). Hatched orange and red zones indicate carbon budgets and mitigation rates that are likely to limit mean warming to 1.5 °C and 2 °C, respectively (see Methods), and stars denote committed emissions and mitigation rates if existing/and proposed infrastructure is operated as historically.

commissioned after 2004; in China and India, the post-2004 capacity is 79% and 69%, respectively. The average age of coal-fired power plants operating in China and India (11.1 and 12.2 years, respectively) is thus much lower than in the USA and EU28 (39.6 and 32.8 years, respectively; Fig. 2b), with correspondingly longer remaining lifetimes. The predominance of young Chinese infrastructure (which extends to the industrial and transportation sectors; Extended Data Figs. 2, 3) reflects the scale and speed of the country's industrialization and urbanization since the turn of the century. As a result, infrastructural inertia is greatest in China, accounting for 41% of all committed emissions (270 Gt CO_2; Fig. 1b). By comparison, infrastructure in India, the USA and the EU28 represents much smaller commitments: 57 Gt, 57 Gt and 49 Gt CO_2, respectively (Fig. 1b, Supplementary Table 1).

In addition to existing infrastructure, new power plants are being planned, permitted or constructed, and the committed emissions related to such proposed plants can be estimated[11,12]. As of the end of 2018, the best available data showed that 579 gigawatts (GW), 583 GW and 40 GW of coal-, gas- and oil-fired generating capacity respectively was proposed to be built over the next few years (some 20% of it in China; Fig. 2). If built and operated as historically, this proposed capacity would represent an additional 188 Gt CO_2 committed: 97 Gt CO_2 from coal-fired and 91 Gt CO_2 from gas-, oil- and other-fuel-fired generating units (Supplementary Table 2).

Together, committed emissions from existing infrastructure and proposed power plants total 846 Gt CO_2 if all proposed plants are built and all infrastructure is operated as historically (Fig. 1).

Existing electricity and industry infrastructure accounts for 79% of total committed emissions if operated as historically (that is, with a 40-year lifetime and 53% utilization rate; Fig. 1a). However, the lifetime and operation of such infrastructure will ultimately depend on the relative costs of competing technologies, which are in turn influenced by factors such as technological progress and the climate and energy policies in each region[22,26]. Figure 3 highlights the sensitivity of committed emissions (Fig. 3a, b) and the rate of annual emissions reductions (Fig. 3c, d; see Methods) with respect to assumed lifetimes and utilization rates (that is, the capacity factors) of industry and electricity infrastructure (note that the lifetimes and operation of infrastructure in other sectors do not vary from historical averages), with the star in each panel indicating historical average values. For example, total committed emissions related to existing infrastructure decrease to around 200 Gt CO_2 if lifetimes are 20 years and capacity factors are 20%, but increase to almost 1,500 Gt CO_2 if lifetimes and capacity factors are respectively 60 years and 80% (Fig. 3a). These ranges of lifetimes and utilization are quite wide, at the low end probably exceeding economic feasibility for recouping capital investments and covering fixed operating and maintenance costs. When proposed power plants are included, total committed emissions over the same range of lifetimes and capacity factors increase to 263–1,906 Gt CO_2 (Fig. 3b). Maintaining historical capacity factors, a 5-year difference in the lifetime of existing infrastructure represents roughly 70–100 Gt of future CO_2 emissions (Fig. 3a), or about 90–130 Gt if proposed power plants are included (Fig. 3b). Maintaining historical lifetimes and changing the assumed capacity factor by a comparable 9% (for example, from 46% to 55%) results in roughly the same changes in committed emissions, suggesting that these factors have a similar influence.

For comparison, the hatched red and orange zones in Fig. 3a, b show the Intergovernmental Panel on Climate Change (IPCC)'s most recent estimated ranges of remaining cumulative carbon budgets that span the 66%–50% probabilities of limiting global warming to 1.5 °C and 2 °C, relative to the preindustrial era[5]. Excluding proposed power plants, our central estimate of committed emissions (658 Gt CO_2; star in Fig. 3a) exceeds the range of the remaining 1.5 °C budget (420–580 Gt CO_2)[5]. When proposed plants are included, our estimate of committed emissions (846 Gt CO_2; star in Fig. 3b) is two-thirds of the lower estimates of the 2 °C budgets (1,170–1,500 Gt CO_2)[5]. This suggests that, unless compensated by negative-emissions technologies or by retrofitting with carbon capture and storage, 1.5 °C carbon budgets allow for no new emitting infrastructure and require substantial changes to the lifetime

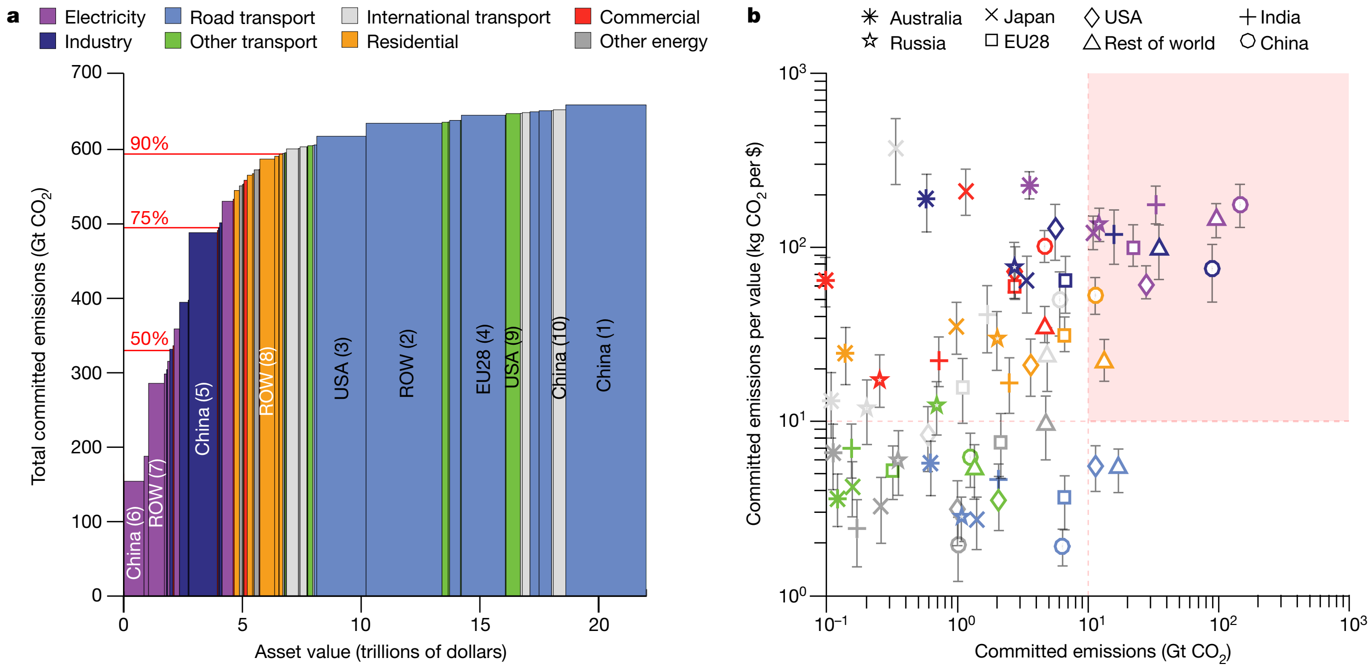

Fig. 4 | Asset value and committed emissions of existing infrastructure. **a**, Rank ordering of CO_2-emitting assets by committed emissions per dollar value reveals large disparities (coloured by sector). The horizontal red lines indicate 50%, 75% and 90% of total committed emissions (658 Gt CO_2) if operated as historically, and the top ten most valuable region sectors are labelled (see Extended Data Fig. 4 for region-specific versions). ROW, rest of world. **b**, Plotting emissions per value (in kilograms of CO_2 per US dollar) against committed emissions suggests targeted opportunities to 'unlock' future CO_2 emissions if alternative technologies become affordable (region sectors in the pink-shaded quadrant). Error bars denote 95% confidence intervals.

or operation of existing energy infrastructure (for example, decreasing lifetimes to less than 25 years or capacity factors to less than 30%; Fig. 3a). Moreover, CO_2 emissions related to the extraction and transport of fossil fuels[27], as well as non-energy CO_2 emissions (for example, resulting from land-use change)[28], are not included in our estimates and will further reduce the remaining carbon budgets.

Climate targets have sometimes been contextualized by the annual rate of emissions reduction they imply. For example, it has been shown[29] that, as of 2013, the cumulative carbon budgets likely to avoid 2 °C of mean warming imply necessary average annual reductions in global CO_2 emissions (that is, mitigation rates) of roughly 6% per year. The hatched areas in Fig. 3c, d show that such mitigation rates, recalculated from the latest carbon budgets, are about 5% per year for the 2 °C budgets (4.5–5.7%) and about 13% per year for the 1.5 °C budgets (11.4–15.7%). By comparison, the contours in the figure show mitigation rates if no new emitting infrastructure is commissioned (10.1%; star in Fig. 3c), or if only already-proposed power plants but no other emitting infrastructure is commissioned (7.9%; star in Fig. 3d). Again, the international targets leave little or no room for new infrastructure if existing plants operate as they have historically (stars), unless fully compensated by negative emissions or retrofitted with carbon capture and storage technology.

Given the constraints of 1.5 °C and 2 °C carbon budgets, we also explore the economic value of existing infrastructure relative to its associated committed emissions. Figure 4a highlights the disproportionality of committed emissions per unit asset value. Together, power and industry infrastructure (purple and dark blue, respectively, in Fig. 4a) represent more than 75% of total committed emissions (519 Gt of 658 Gt CO_2), but less than 25% of the estimated economic value of CO_2-emitting energy infrastructure (roughly US $5 trillion of US $22 trillion; Extended Data Fig. 4 and Supplementary Table 3; see Methods for details of how asset values were amortized). By contrast, transportation infrastructure, with shorter average lifetimes but high capacity costs and a vast number of discrete units, represents roughly two-thirds of the value of emitting assets and less than 10% of committed emissions (Fig. 4a). This analysis suggests that efforts to reduce committed emissions might cost-effectively target the early retirement of electricity and industry infrastructure—despite their often powerful influence on policy and institutions[6,21,22]—if non-emitting alternative technologies are affordable: the magnitude of commitments in these sectors is large and a single dollar of asset value is related to more than 10 kg of future CO_2 emissions (Fig. 4b, red rectangle). Industry and electricity sectors in China represent especially prime targets for unlocking future emissions: nearly half (46%) of these sectors' global committed emissions are associated with Chinese infrastructure (Fig. 4a).

Detailed and up-to-date analysis of existing and proposed CO_2-emitting energy infrastructure worldwide reveals incredibly tight constraints for present international climate targets, even if no new emitting infrastructure is ever built. Although climate and energy analysts have emphasized that avoiding, for example, 1.5 °C of warming remains "technically possible"[5], our results lend vivid context to that possibility: we would have a reasonable chance of achieving the 1.5 °C target with, first, a global prohibition of all new CO_2-emitting devices (including many or most of the already-proposed fossil-fuel-burning power plants); and second, substantial reductions in the historical lifetimes and/or utilization rates of existing industry and electricity infrastructure.

Barring such radical changes, the global climate goals adopted in the Paris Agreement are already in jeopardy and may be contingent upon widespread retrofitting of existing emitting infrastructure with carbon capture and storage technologies (which would be tremendously expensive[30]), large-scale deployment of negative emissions technologies[16], and/or solar-radiation management[4]. On the other hand, our results suggest that the precise level of future warming in excess of the Paris targets depends largely on infrastructure that has not yet been built (Extended Data Fig. 5).

Some important caveats and limitations apply to our findings. The trajectory of future emissions depicted in Fig. 1 represents a scenario in which existing (and proposed) emitting infrastructure 'ages out', and no new emitting infrastructure is ever commissioned. These constraints are not intended to be realistic; rather, they allow us to isolate and quantify infrastructural—and related economic—lock-in of energy-related emissions[22]. Indeed, technological trends and climate-energy policies that encourage growth in renewable electricity (for example, solar and wind) may lead to early retirement of existing fossil-fuel power plants in some regions (although recent growth of renewable electricity generation has not always displaced fossil-fuel generation[18]). It is also instructive to compare our estimates of committed emissions with plausible energy-emissions scenarios generated by much more sophisticated (but less transparent) IAMs that calculate infrastructure lifetimes and capacity factors endogenously. For example, a recent IAM study of 1.5 °C scenarios found that large-scale CO_2 removal may be necessary to compensate for 'residual' emissions from long-lived and difficult-to-decarbonize sectors of the energy system (for example, freight, aviation and shipping[4])[31].

The size of carbon budgets associated with a given temperature target is also a complicated matter that is sensitive to a host of factors, such as climate sensitivity and non-CO_2 emissions[14,15]. The budgets from the recent IPCC special report[5] are estimates of cumulative net global anthropogenic CO_2 emissions from the start of 2018 until net-zero global CO_2 emissions are achieved (that is, climate is stabilized) with a 66%–50% probability of limiting an increase in mean near-surface air temperatures to 1.5 °C or 2 °C, with limited (less than 0.1 °C) or no overshoot (see Methods for further discussion).

Although ambitious climate targets such as 1.5 °C may help to motivate and accelerate the transition towards net-zero energy systems, their feasibility is often evaluated by the existence of consistent scenarios from IAMs. However, these models have been used to analyse a very large possibility space, and some scenarios may thus reflect aspirational trajectories of energy demand or technological progress and scale whose likelihood may be difficult to evaluate[32,33]. Our data-driven assessment of existing, operating and valuable energy infrastructure may therefore help to elucidate the infrastructural and economic implications of such targets, and also help to identify targeted regional and sectoral opportunities for unlocking future CO_2 emissions.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, statements of code and data availability and associated accession codes are available at https://doi.org/10.1038/s41586-019-1364-3.

Received: 2 December 2018; Accepted: 10 May 2019;
Published online 1 July 2019.

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Acknowledgements D.T. was supported by NASA's Interdisciplinary Research in Earth Science (IDS) programme (80NSSC17K0416) and the National Natural Science Foundation of China (41625020). Q.Z. was supported by the National Natural Science Foundation of China (41625020). C.H., Y.Q. and S.J.D. were supported by the US National Science Foundation (Innovations at the Nexus of Food, Energy and Water Systems (INFEWS) grant EAR 1639318).

Reviewer information *Nature* thanks Gunnar Luderer, Katsumasa Tanaka and the other anonymous reviewer(s) for their contribution to the peer review of this work.

Author contributions S.J.D., D.T. and Q.Z. designed the study. D.T. performed the analyses, with support from Q.Z., Y.Z. and C.S. on datasets, and from S.J.D., Q.Z., K.C., C.H. and Y.Q. on analytical approaches. D.T. and S.J.D. led the writing with input from all coauthors.

Competing interests The authors declare no competing interests.

Additional information
Extended data is available for this paper at https://doi.org/10.1038/s41586-019-1364-3.
Supplementary information is available for this paper at https://doi.org/10.1038/s41586-019-1364-3.
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METHODS

Committed emissions from existing and proposed infrastructure. We extend the approach of ref. [9] to quantify the committed emissions from existing energy infrastructure by integrating more-detailed and up-to-date available data on energy infrastructure, including country- and duty-specific vehicle sales data, and unit-level details on global power plants and Chinese cement kilns and blast furnaces[10,34–39]. We also estimate committed emissions from proposed power plants by collecting information on all proposed power generators from the latest available databases[34,37], in recognition of substantial changes in the pipeline of planned power plants (especially coal) in recent years[34]. Energy infrastructure as quantified in this study is categorized into eight sectors: (1) electricity, (2) industry, (3) road transport, (4) other transport, (5) international transport, (6) residential, (7) commercial and (8) other energy infrastructure (see Supplementary Tables 4 and 5).

Electricity infrastructure. Emissions from electricity infrastructure in this study include all emissions under category 1A1 of the IPCC's revised guidelines[40]. Electricity infrastructure here mainly includes main activity electricity and heat production (1A1a) and petroleum refining (1A1b), as well as the manufacturing of solid fuels and other energy industries (1A1c) (Supplementary Table 5).

Emissions intensities of electricity infrastructure. Previously, we built and published a comprehensive global thermal power plants database (named the Global Power Emissions Database, or GPED) of the year 2010 by integrating high-quality national databases (from China, India and the USA)[10]. Here we update the GPED database to the year 2018 (named GPED-2018) using the latest power plant database from China (CPED)[36] and the Platts World Electric Power Plant (WEPP) database for other regions[37], including all retired and operating units through to the end of 2018. We obtain data and estimates of unit-based CO_2 emission intensity (that is, grams CO_2 per kilowatt-hour) for all units that were operating in 2010 from GPED. For units retired before 2010 or commissioned since 2010, we estimate unit-level CO_2 emission intensity by the methods of ref. [9] on the basis of the Carbon Monitoring for Action (CARMA) database[35] (for older units), or else use national or regional average CO_2 emission intensity for units with the same fuel type and similar nameplate capacity. As prior studies have done, we assume these emissions intensities are constant over a unit's lifetime[8,9].

Assumed lifetime of electricity infrastructure. In the resulting GPED-2018, the global average lifetimes of retired coal-, natural-gas- and oil-fired power units are 35.9, 37.1 and 33.9 years, respectively. Consistent with ref. [9], we simplify these ranges to a single reference lifetime of 40 years for all electricity-generating units for our 'as historically' case, and show the sensitivity of committed emissions to this assumption in Fig. 3. When units are already operating beyond their assumed lifetime, we randomly retire them over the next five years in order to avoid unrealistically abrupt changes in emissions between 2018 and 2019.

In addition, we assume that the age structure and lifetime of autoproducers (industrial and commercial facilities that generate their own electricity on-site)[40] and other energy industries are similar to the main-activity power plants in each region. Therefore, committed emissions from existing electricity infrastructure are quantified by using the survival curves derived from main-activity power plants, scaled to include these other types of electricity infrastructure by using country-level electricity emissions totals in 2018 from the International Energy Agency (IEA). Note that, because of data availability[41], we derived the country-level CO_2 emissions from fossil-fuel combustions for 2018 by multiplying country-level CO_2 emissions in 2016 by projected change rates during 2016–2018.

Finally, we quantify cumulative future CO_2 emissions from proposed power plants by the same procedure (assuming historical average unitization rates and lifetimes), using a database of proposed coal-fired units that has been developed by CoalSwarm[34] and the planned units fired with other fossil fuels from the 2018 (fourth quarter) WEPP database[37].

Industry infrastructure. Industrial emissions in this study include all emissions under category 1A2 of the IPCC's revised guidelines[40]. For all countries but China, we estimate cumulative future emissions from industry infrastructure by using country-level emissions data for the year 2018 obtained from the IEA, assuming that the age distribution and survival curves of each region's industry infrastructure are consistent with its electricity infrastructure. To derive China's industrial survival curves, we use unit-level details of cement kilns and blast furnaces (iron and steel) that are currently operating in China (Extended Data Fig. 2), obtained from China's Ministry of Ecology and Environment (MEE) (our unpublished data, referred to hereafter as the MEE database).

Our detailed data on Chinese infrastructure represent an important improvement over prior estimates of committed emissions, as China alone accounts for roughly 47% of total industrial emissions[41]. In particular, the iron/steel and non-metallic minerals (for example, cement and glass) industries account for about 50% of all industrial CO_2 emissions in recent years[41], and China produced 49.6% of the world's raw steel and 57.3% of the world's cement in 2016 (ref. [42]). The unit-level data on China's industrial infrastructure thus substantially decrease the uncertainty of committed industry emissions, by alleviating the need for assumptions related to almost half of global industry infrastructure (that is, 9.0% of global CO_2 emissions from all sources[41]). Moreover, we observe that the age distributions of electricity and industry infrastructure in China are quite similar (Extended Data Fig. 6), which lends support to our assumption that this is the case in other regions for which we lack detailed data on industrial infrastructure.

Transportation infrastructure. Transport emissions in this study include all emissions under category 1A3 of the IPCC's revised guidelines[40], which includes emissions from road transport, other transport and international transport (Supplementary Tables 4, 5).

We calculated cumulative future emissions from road transport following the approach in ref. [8] and further updating the activity rates with updated country-, region- and duty-specific vehicle sales data[38,39] (that is, 18% of global CO_2 emissions from all sources[41]). Specifically, we use the number, class and vintage of motor vehicles sold during 1977–2017 from 40 major countries and regions[38,39] (information for 2018 was derived by projecting 2016–2017 rates of change one additional year; Extended Data Fig. 3). Owing to data availability, we estimate the number of vehicles remaining on the road over time by using class and model year-specific survival rates of US and Chinese vehicles to represent developed (the USA) and developing (China) countries or regions[43,44]. We then calculate annual vehicle emissions by using the average miles driven per year (MPY) per vehicle by class, and carbon emission factors of 10.23 kg and 11.80 kg CO_2 per gallon of gas and diesel, respectively, and scale our estimated emissions to match country-level road-transport emissions in 2018 as reported by the IEA[41].

'Other transportation' infrastructure includes existing aviation, rail, pipeline, navigation and other non-specified transport. International transport infrastructure includes international marine bunkers and international aviation bunkers (Supplementary Table 4). Again, we follow ref. [8], estimating cumulative future CO_2 emissions from existing other and international transport by using country-level emissions data for 2018 from IEA, and assuming lifetimes and age distributions similar those of to motor vehicle fleets in each country/region.

Residential, commercial and other energy infrastructure. Residential and commercial emissions are included under category 1A4 of the IPCC's revised guidelines[40], and 'other energy' emissions include, for example, emissions from agriculture, forestry, fishing and aquaculture under category 1A4, as well as stationary, mobile and multilateral operations under category 1A5. We calculated cumulative future emissions from this infrastructure by using country-level emissions data for 2018 derived from the IEA[41], and assuming that age distributions and lifetimes of residential, commercial and other energy infrastructure in each region were similar to electricity infrastructure in the same region in the absence of better information.

The least-supported methodological assumptions that we make thus concern this residential, commercial and other energy infrastructure (representing around 10% of total fossil fuel CO_2 emissions in 2016; ref. [41]), where we lack any unit-level data. In order to test the sensitivity of total committed emissions from this infrastructure, we performed additional analyses of different assumed lifetimes. We found the committed emissions from residential, commercial and other energy infrastructure to be 29, 74 and 135 Gt CO_2 when lifetimes of respectively 20, 40 and 60 years are assumed (Extended Data Fig. 7). That is, our estimates of total committed emissions from all existing energy infrastructure decrease by 7% (to 613 Gt CO_2) if lifetimes of residential, commercial, and other energy infrastructure are assumed to be 20 years, and increase by 9% (to 719 Gt CO_2) if the lifetimes are assumed to be 60 years. In comparison with the carbon budgets associated with targets of 1.5 °C and 2 °C, these are relatively small effects, and not substantial enough to affect the main conclusions of our study.

Comparison of cumulative future emissions estimates. Other studies[8,9,11–13] have analysed committed emissions from various infrastructures in different ways, as mentioned in the text and summarized in Extended Data Table 1.

For example, refs [11,12] both reported committed emissions relating to existing and planned power plants using 2016 data. Although the latter analysed committed emissions from all fossil electricity infrastructure[12], the former focused particularly on coal-fired units[11]. Importantly, the 2018 data used herein reveal that substantial cancellations of proposed plants have occurred over the intervening two years: whereas the previous studies estimated that around 150 Gt CO_2 (ref. [11]) and 210 Gt CO_2 (ref. [12]) were committed by proposed coal plants, we estimate only around 100 Gt CO_2—that is, 50–100 Gt CO_2 less (or 10%–20% of the remaining carbon budget that is consistent with 1.5 °C warming). Moreover, our study contains more-detailed estimates of regional commitments and the sensitivity of these commitments to assumed lifetime and capacity factor.

Most recently, ref. [13] estimated the global warming related to committed emissions by using a reduced-complexity climate model (Finite Amplitude Impulse Response, or FaIR). Their study also included estimates of committed emissions from all sectors, but these relied on past estimates of the age distribution of fossil-fuel infrastructure and an idealized, linear phase-out of such infrastructure[13]. Because turnover of infrastructure has decreased the median age of electricity-generating capacity in many regions (Fig. 2), our estimates of electric power sector commitments (358 Gt CO_2) are about 13 Gt CO_2 greater than those used in ref. [13] (345 Gt CO_2). Our data-driven approach also permits region-specific results, analysis of the trend in commitments over time, inclusion of proposed power plants, and an assessment of the economic value of underlying infrastructures. Yet, because the estimates of CO_2 emissions committed by other infrastructure in ref. [13] are larger than our bottom-up estimates (Extended Data Table 1), the overall estimate reached by their idealized approach (715 Gt CO_2) is nonetheless similar to ours (658 Gt CO_2).

The authors of ref. [13] assess global climate responses to committed CO_2 increases and conclude that the world is not yet committed to a 1.5 °C warming. However, it is difficult to directly compare the magnitude of the CO_2 emissions in the phase-out scenarios of ref. [13] with the 1.5 °C carbon budgets in the IPCC's special report[5] (SR1.5), for two reasons. First, although SR1.5 also used the FaIR model in its procedure for evaluating non-CO_2 forcing, it did not use the FaIR model's transient climate response to cumulative emissions (TCRE), which is smaller and would have led to considerably larger carbon budgets. Second, the mitigation scenarios evaluated ref. [13] also assumed that non-CO_2 emissions are completely phased out in parallel to CO_2 emissions, but the integrated assessment model scenarios on which SR1.5's non-CO_2 forcing (and carbon budgets) are based do not completely eliminate non-CO_2 emissions this century[45].

Variation in utilization rates and assumed lifetimes. As described above, cumulative future committed emissions from electricity and industry infrastructure depend on present utilization rates and assumed lifetimes. The longer the assumed lifetime and higher the utilization, the greater the estimate of committed emissions will be. Therefore, we test the sensitivity of committed emissions to assumed lifetimes and utilization rates of energy and industry infrastructure across lifetimes from 20 years to 60 years, and utilization rates of 20% to 80%.

Remaining carbon budgets to limit mean warming to 1.5 °C and 2 °C. As described in the text and discussed in recent literature, the size of carbon budgets associated with a given temperature target is a complicated matter that is sensitive to a host of factors[14,15], including: (1) whether the budget reflects cumulative net emissions until the temperature target is exceeded, or cumulative net emissions that limit the global temperature increase to below the target (that is, climate is stabilized); (2) whether there can be a temporary overshoot of the temperature target (and by how much)[46]; (3) the climate responses to CO_2 and non-CO_2 forcings[47]; (4) the magnitude and Earth-system response to negative emissions[48]; (5) how global temperature is calculated; (6) the pre-industrial baseline used[49]; (7) whether Earth-system feedbacks such as permafrost thawing are included[50–53]; and (8) future emissions of non-CO_2 greenhouse gases and aerosols[54,55].

The magnitude of non-CO_2 forcing is particularly relevant to assessments of committed emissions, because non-CO_2 forcing is inversely related to the remaining carbon budget[54,55], and because some non-CO_2 greenhouse gases and aerosols are directly related to the current energy system (for example, fugitive methane[56]) or are co-emitted with CO_2 by fossil-fuel-burning infrastructure. Other large sources of non-CO_2 gases and aerosols exist outside of the energy system, such as agriculture[57]. For the SR1.5 budgets[5], non-CO_2 forcing was estimated using integrated assessment model scenarios and a pair of reduced-complexity climate models (Model for the Assessment of Greenhouse-gas Induced Climate Change (MAGICC) and FaIR), with substantial uncertainties associated with both scenario variations (± 250 Gt CO_2) and climate responses (−400 Gt to 200 Gt CO_2) for the 1.5 °C budget. Non-CO_2 greenhouse gases and aerosols decline but do not reach zero in any of the scenarios assessed in the SR1.5 report. By contrast, ref. [13] modelled the complete phase-out of non-CO_2 emissions in parallel with energy-related CO_2 emissions—a formidable scenario that was found to have a high probability (64%) of limiting warming to 1.5 °C.

In this study, we compare our estimates of committed emissions to the SR1.5 budgets[5]. As defined in SR1.5, 'remaining' carbon budgets are the cumulative net global anthropogenic CO_2 emissions from a given start date (1 January 2018) to the year in which such emissions reach net zero that would result, at some probability, in limiting global warming to a given level[5]. By this definition, budgets are not simply cumulative emissions until the time at which mean temperature exceeds a given threshold[14], but rather what have been called 'threshold avoidance' or 'stabilization' budgets. The SR1.5 budgets were derived from the transient climate response to cumulative CO_2 emissions in climate model simulations that have been further adjusted to include additional climate forcing related to non-CO_2 greenhouse gases and aerosols[45]. They do not include Earth-system feedbacks (which SR1.5 suggests could reduce the remaining budgets by 100 Gt CO_2 over this century).

However, as remaining budgets associated with a mean surface warming of 1.5 °C dwindle, uncertainties in transient climate responses to CO_2 emissions[15,47] and the current and future non-CO_2 forcing loom large[53–55]. In order to make our results as useful, transparent and comparable as possible, we report positive, CO_2-only commitments from existing and proposed fossil-fuel-burning infrastructure, and compare these to the remaining (stabilization) carbon budgets reported by SR1.5 to give a 66%–50% probability of limiting warming to 1.5 °C and 2 °C with little (0.1 °C) or no overshoot: that is, 420–580 Gt CO_2 and 1,170–1,500 Gt CO_2, respectively (see table 2.2 in ref. [5]). Thus, if not offset by negative emissions, the total committed emissions that we estimate if existing infrastructure operates as it has historically (that is, 658 Gt CO_2) would make it likely that global temperatures will exceed 1.5 °C unless the remaining carbon budgets in SR1.5 are substantially wrong. For example, the climate response to CO_2 could be less than expected on the basis of the climate model simulations assessed in SR1.5, and/or non-CO_2 forcing in the future could be much less than it is on average in the integrated assessment model scenarios that were assessed by SR1.5. Indeed, ref. [13] analysed a future in which both are true.

Estimates of the annual rate of emission reductions. We estimate annual rates of emissions reduction ('mitigation rates') following ref. [29]:

$$f(t) = f_0 (1 + (r + m)t) \exp(-mt)$$

where $f(t)$ is the emissions at time t; f_0 is the emissions at the start of mitigation ($t = 0$); r is an initially linear growth rate; m is the annual rate of emission reductions; and r and m both have units of 'per year'. We calculate the annual rate of emission reductions needed to meet a quota, q, from $t = 0$ onward (with emission time $T = q/f_0$) as:

$$m(q) = \frac{1 + \sqrt{1 + \frac{rq}{f_0}}}{\frac{q}{f_0}} = \frac{1 + \sqrt{1 + \frac{r}{T}}}{T}$$

We use initial emissions, f_0, at 2018 (32.7 Gt) and growth rates, r, averaged over 2013–2018 (0.028%) (obtained from the IEA[41]) to estimate mitigation rates under different cumulative CO_2 emissions, which we assumed to be equivalent to the carbon quota, q.

Estimates of asset value from existing infrastructure. We estimate the asset value by sector and by country/region using the following equation:

$$\mathrm{AV}_{i,s} = \sum_{n=\mathrm{PY}-\mathrm{LT}}^{\mathrm{PY}} \sum_{y} \{\mathrm{TC}_{i,s,n,y} \times \mathrm{CC}_{i,s,n,y} \times [(1-\mathrm{RV}) \times \mathrm{DR}_{i,s,n,y} + \mathrm{RV}]\}$$

where i, s, n and y represent the country/region, sector, years and combustion/production technology, respectively; AV is the asset value; TC is the equivalent total capacity/numbers; CC is the capital costs; RV is the ratio of residual value, with 5% applied for all infrastructure; DR is the depreciation rate; PY is the present year (2018 in this study); and LT is lifetime.

We adopt a sector-dependent method, and apply straight-line and geometric models for different infrastructures, as in Supplementary Table 6. We collected data on capital costs used to estimate asset values from previous literature[12,21,23–25,58,59] and various reports[60–64]. Wherever possible, we use interannual and national average capital costs for different combustion/production technologies and equipment. Where interannual and national averages are not available, we instead use an average for all of the countries in the same region for which capital cost data are available.

Electricity infrastructure. We estimate the total value of fossil-fuel-based electricity-generating assets according to each unit's power-generating capacity (in kilowatts) and age, as well as fuel- and technology-specific capital costs (in dollars per kilowatt).

The assumed lifetime of coal power plants is 40 years. Although plants can operate for considerably longer periods, shutting down a plant after its assumed lifetime will not result in any stranded capital investment, since the initial capital cost will have been fully paid[24]. Thus, our estimates only include the asset value of operating electricity-generating units that are now less than 40 years old. Unit-level details of electricity-generating technologies were obtained from the GPED-2018 database.

In addition, part of the committed CO_2 emissions in electricity infrastructure is from heating plants. We have evaluated the asset value of combined heat and power (CHP) plants along with that of other power plants, but we estimate the asset value of individual heating plants separately, using IEA data on heating output (in terajoules, TJ)[65,66] to estimate the capacity of such heating plants and converting this to an equivalent power capacity (in GW) by assuming that they operate with the average utilization rates of power-generating units in the same region. Supplementary Table 6 summarizes our assumptions in estimating asset values for individual heating plants.

Industrial infrastructure. 'Industrial infrastructure' includes various facilities and systems from different subindustrial sectors (Supplementary Tables 4 and 5). Considering the difficulty of collecting the operating capacity for all of the subindustrial sectors, we estimate the value of industry infrastructure as the combined asset values of cement, iron and steel plants, and industrial boilers. As described above, we estimated the asset values for cement, iron and steel capacity that has been operating less than 40 years only. We quantified asset values from the cement, iron and steel industries through total capacity and capital investment per unit (Supplementary Table 6).

We estimate total capacities (in tonnes per hour, t h^{-1}) of industrial boilers at country- or region-specific level by fuel type, using total energy consumptions obtained from the IEA[65,66]. We assume the utilization rates of industrial boilers to be the same as the average utilization rates of electricity infrastructure. The related assumptions are shown in Supplementary Table 6.

Transport infrastructure. We quantify the asset values from road transport, other transport and international transport separately. For road-transport infrastructure, we estimate asset value using the number of annual vehicle sales, annual average new car prices, and a depreciation-rate function. The data sources for the number of annual vehicle sales are described above, and we further collect annual average new car prices by vehicle type and country/region[39]. Because depreciation rates tend to be considerably lower in developing countries than in industrialized countries[67], we adopt different depreciation-rate functions for developing and developed countries[67].

For international-transport infrastructure, we estimate the value of international ships and international airplanes. Owing to limited data availability, we use the same approach as with heating infrastructure, basing our estimates on the total energy consumption (fuels) for international aviation and international navigation from the IEA, and converting to the number of reference narrow-body aircraft and standardized international freight ships by such fuel consumption. Specifically, we assume 2 million kilometres per year for each aircraft, and 149 megajoules per airplane kilometre, for reference narrow-body aircrafts[21] (Supplementary Table 6); and 940 million annual tonnes per kilometre, and an average ship energy intensity of 0.125 megjoules per tonne kilometre, for international freight ships[21]. We use the same total average depreciation rates for international transport as we do for road-transport infrastructure.

We use a similar approach for other transport (that is, domestic ships, domestic airplanes and non-specific transport), adopting the same assumptions applied for international transport for domestic ships and domestic airplanes. For non-specific transport, we quantify asset values by converting to the number of conventional diesel heavy-duty freight trucks. The corresponding assumptions are shown in Supplementary Table 6.

Residential, commercial and other energy infrastructure. We quantify the asset values of residential, commercial and other energy infrastructure separately using sector- and fuel-specific energy-consumption data from the IEA[65,66].

Residential and commercial infrastructure uses energy for space heating, heating water, and cooking. Other energy infrastructure includes uses of energy for agriculture, fishing and other activities. Given very limited data, we quantify the value of residential and commercial infrastructure by using an equivalent capacity of normalized space heating units, water-heating units and cooking equipment. For the 'other energy' infrastructure, we quantify the asset value by converting to normalized agriculture machines, fishing boats and boilers. We then apply the total average depreciation rates of electricity infrastructure to these residential, commercial and other energy infrastructures.

Uncertainty estimation. Our estimates of asset values are subject to uncertainty owing to incomplete knowledge of operating capacities, age structure and capital costs per unit. In order to more completely assess uncertainties in our results, we perform a Monte Carlo analysis of asset values by sector and by country/region, in which we vary key parameters according to published ranges[58,68,69] and collected capital costs data as above. The error bars in Fig. 4 depict the results of this analysis, showing the lower and upper bounds of a 95% confidence interval (CI) around our central estimate. The Monte Carlo simulation uses specified probability distributions for each input parameter (for example, capital cost per unit, and the ratio of residual value) to generate random variables[68]. The probability distribution of asset values is estimated according to a set of runs ($n = 10{,}000$) in a Monte Carlo framework with probability distributions of the input parameters. The ranges of sector and region parameter values vary in part because of the quality of their statistical infrastructures[69]. Supplementary Table 7 summarizes the probability distributions of the asset value estimation-related parameters.

Data availability

The numerical results plotted in Figs. 1–4 are provided with this paper. Our analysis relies on six different data sets, each used with permission and/or by license. Five are available from their original creators: (1) the GPED database: http://www.meic-model.org/dataset-gped.html; (2) Platt's WEPP database: https://www.spglobal.com/platts/en/products-services/electric-power/world-electric-power-plants-database; (3) the Carbon Monitoring for Action (CARMA) database: http://carma.org/; (4) the CoalSwarm database: https://endcoal.org/tracker/; and (5) vehicle sales data: https://www.statista.com/markets/419/topic/487/vehicles-road-traffic/. The sixth data set includes unit-level data for Chinese iron, steel and cement infrastructure, which we obtained directly from the Chinese Ministry of Ecology and Environment. We do not have permission to share the raw data, but we provide it in an aggregated form (Extended Data Fig. 2).

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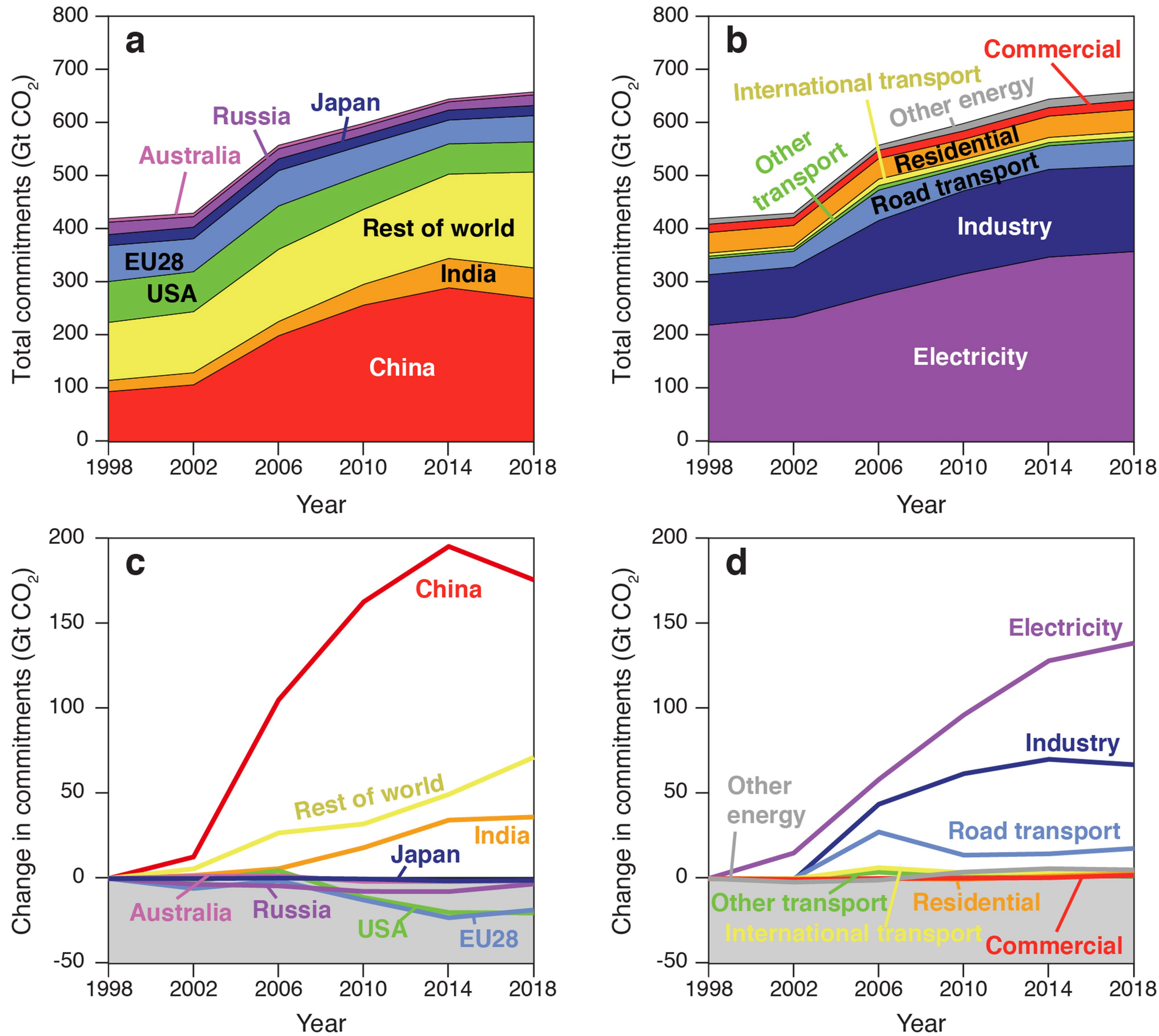
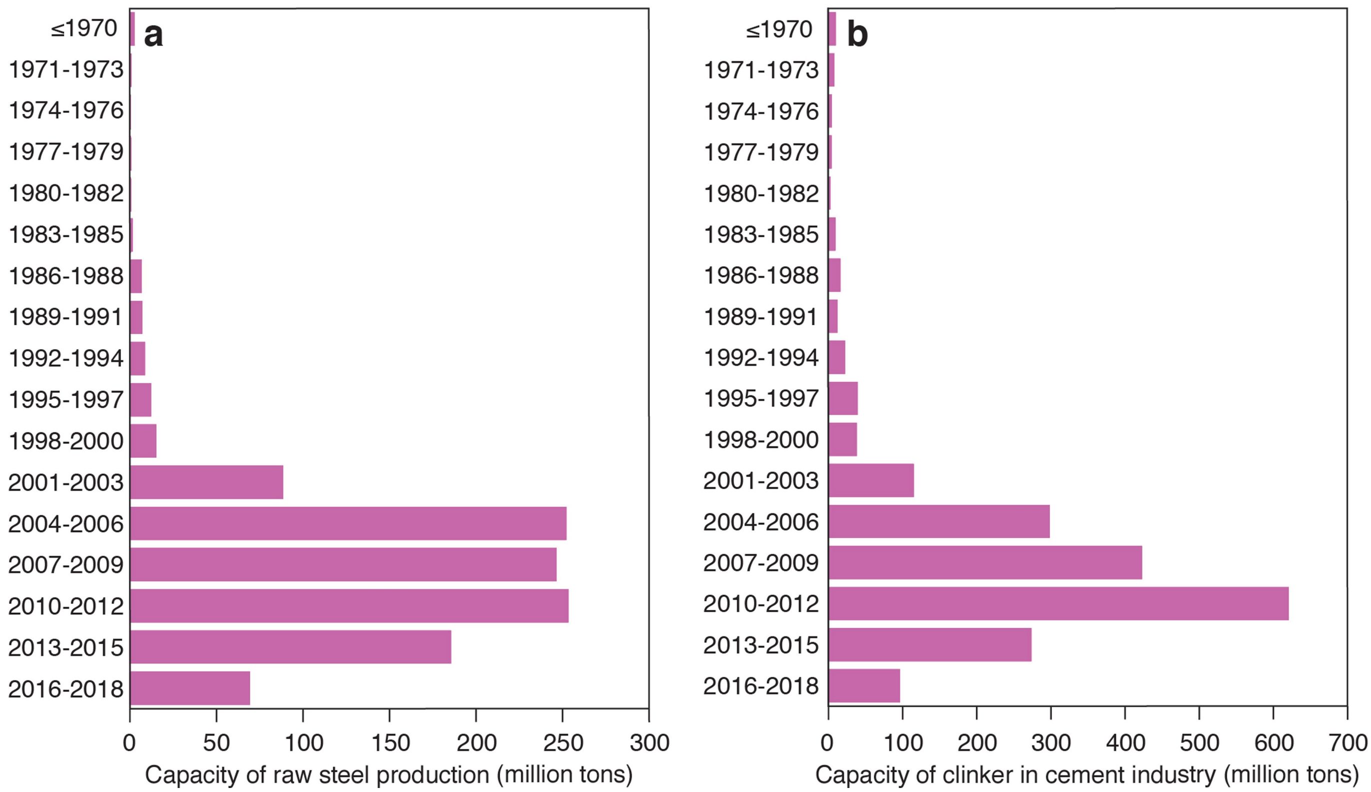
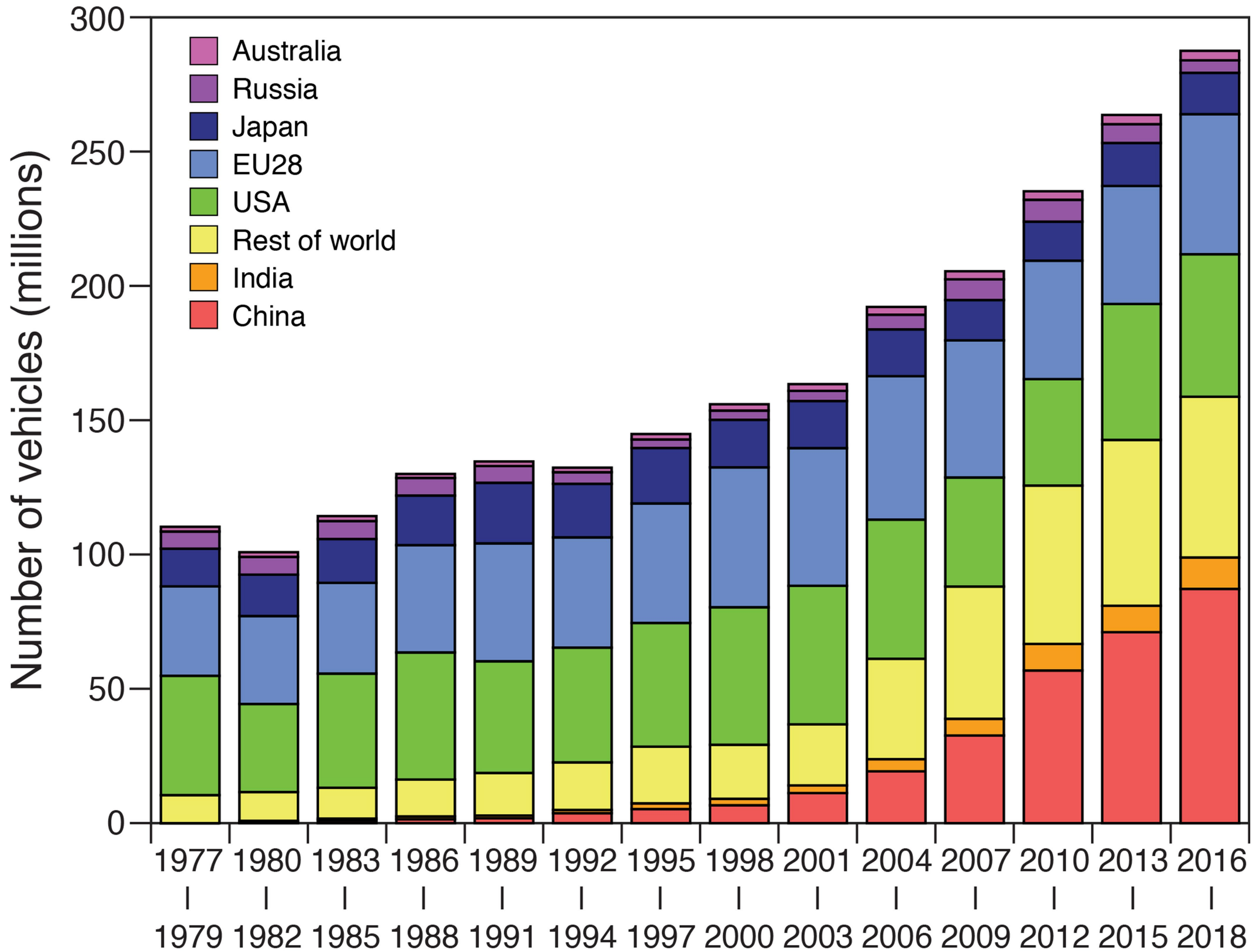


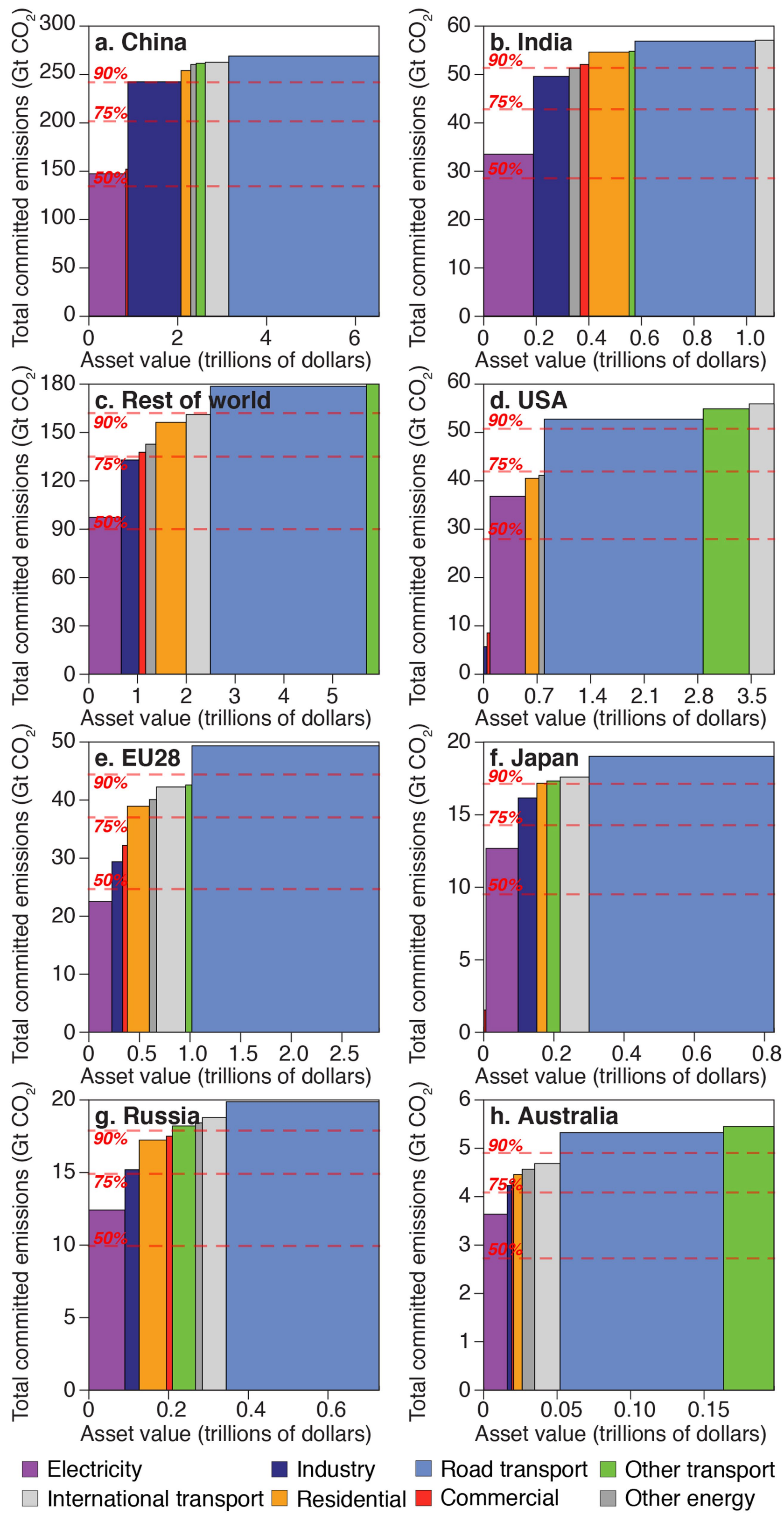
Extended Data Fig. 1 | Changes in commitments from existing energy infrastructure. **a**, **b**, Estimates of future CO_2 emissions every four years (1998, 2002, 2006, 2010, 2014 and 2018) by industry sector (**a**) and country/region (**b**), assuming historical lifetimes and utilization rates. **c**, **d**, Corresponding changes in remaining commitments by industry sector (**c**) and country/region (**d**).



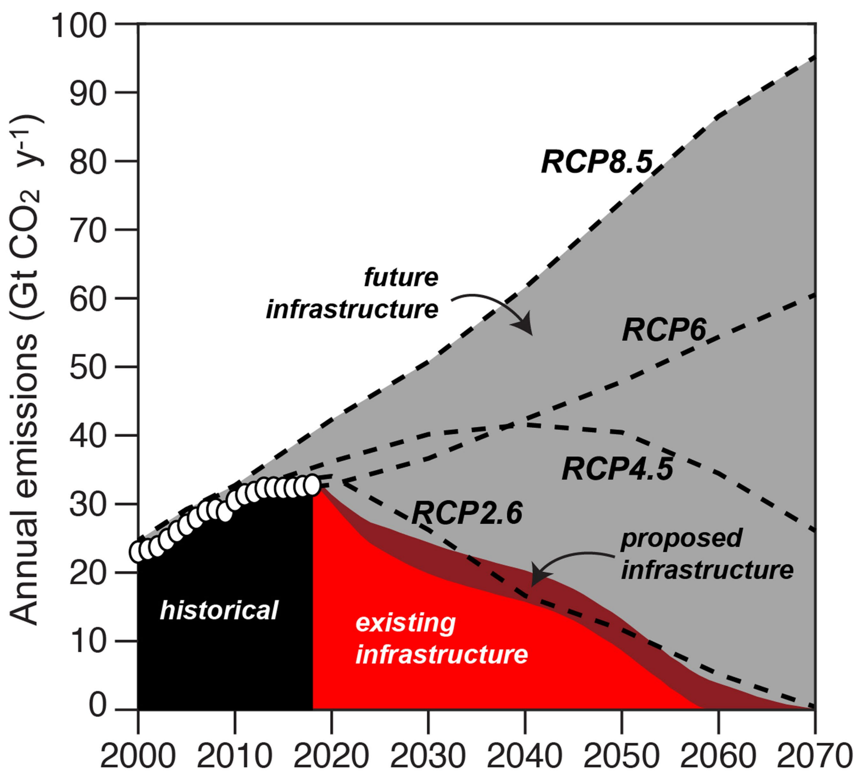
Extended Data Fig. 2 | Age structure of Chinese major industrial capacity. a, **b**, The operating capacity of raw steel in the iron and steel industry (**a**) and clinker in the cement industry (**b**). The youngest units are shown at the bottom.



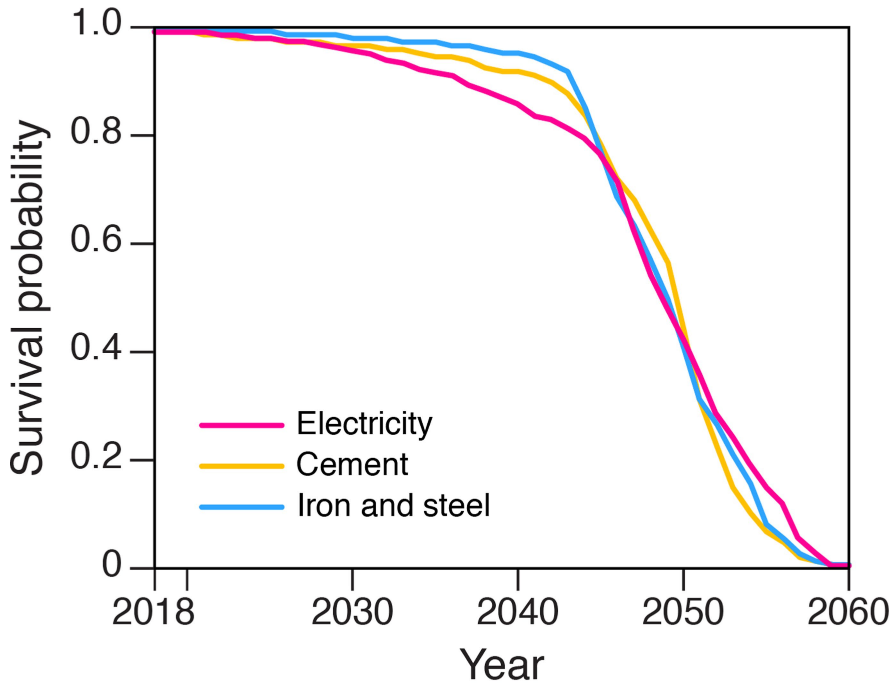
Extended Data Fig. 3 | Age structure of existing road-transport infrastructure. This figure shows the numbers of vehicle sales by country/region.



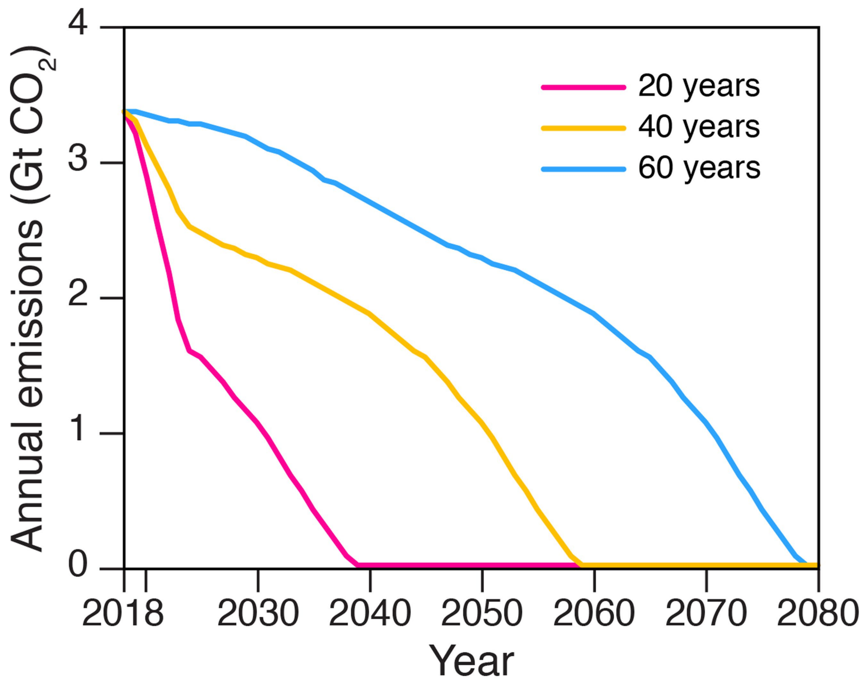
Extended Data Fig. 4 | Asset values and committed emissions for existing infrastructure. Total committed emissions are plotted against asset value, by country/region and sector. Dashed horizontal lines indicate 50%, 75% and 90% of total committed emissions if operated as historically.



Extended Data Fig. 5 | Annual emissions from existing, proposed and future infrastructure. The figure shows historical CO_2 emissions from fossil-fuel energy infrastructure (black), and future CO_2 emissions from existing (red) and proposed (dark red) energy infrastructure, as well as future infrastructure (dark grey) under particular representative concentration pathways (RCPs: RCP8.5, RCP6, RCP4.5 and RCP2.6).



Extended Data Fig. 6 | Survival curves for power and major industries in China. This figure shows survival curves for the electricity sector, cement industry, and iron and steel industry in China under the assumption of 40-year lifetimes.



Extended Data Fig. 7 | Annual emissions from residential, commercial and other energy infrastructure. The figure shows future annual CO_2 emissions from residential, commercial and other energy infrastructure under the assumptions of 20-, 40- and 60-year lifetimes.

Extended Data Table 1 | Comparison of committed emissions

		Ref. 8		Ref. 9		Ref. 11		Ref. 12		Ref. 13		This study	
		Gt CO_2	Year of dataset	Gt CO_2	Year of dataset	Gt CO_2	Year of dataset	Gt CO_2	Year of dataset	Gt CO_2	Year of dataset	Gt CO_2	Year of dataset
Existing	Electricity	224	2009	307	2012	-	-	308	2016	345 (261-451)	2009*	358 (240-493)†	2018
	Coal		2009	206	2012	190	2016	220	2016	-	-	260 (175-358)	2018
	Gas, oil, and other fuels		2009	100	2012	-	-	88	2016	-	-	98 (65-135)	2018
	Industry	104	2009			-	-	-	-	154 (117-191)	2009	162 (110-219)	2017
	Transport	116	2009			-	-	-	-	92 (73-110)	2017	64 (53-75)	2017
	Residential, commercial, and other energy	53	2009			-	-	-	-	121 (91-158)	2009	74 (52-105)	2018
	All Sectors	**496 (282-701)**				-	-	-	-	**715 (546-909)**	-	**658 (455-892)**	-
Proposed	Electricity					-	-	271	2016	-	-	188 (142-234)	2018
	Coal					150	2016	210	2016	-	-	97 (74-121)	2018
	Gas, oil, and other fuels					-	-	61	2016	-	-	91 (68-113)	2018
All Sectors + Proposed Electricity												**846 (597-1,126)**	

Comparison of committed emissions by sector, estimated here and previously[8,9,11–13]. Note that, in some cases, the totals may not correspond to the sum of the underlying sectors, owing to rounding.
*The age distribution of infrastructure is the same as in 2009, but annual emissions from the infrastructure were adjusted up to 2018 levels.
†The range represents the committed emissions estimated under the assumption of 30–50-year lifetimes for all sectors except transportation (12–18-year lifetimes).