Future CO₂ Emissions and Climate Change from Existing Energy Infrastructure

Steven J. Davis,¹* Ken Caldeira,¹ H. Damon Matthews²

Slowing climate change requires overcoming inertia in political, technological, and geophysical systems. Of these, only geophysical warming commitment has been quantified. We estimated the commitment to future emissions and warming represented by existing carbon dioxide-emitting devices. We calculated cumulative future emissions of 496 (282 to 701 in lower- and upper-bounding scenarios) gigatones of CO₂ from combustion of fossil fuels by existing infrastructure between 2010 and 2060, forcing mean warming of 1.3°C (1.1° to 1.4°C) above the pre-industrial era (or 0.3° to 0.7°C greater than at present; Fig. 1). Cumulatively, we estimate that 496 (282 to 701 in lower- and upper-bounding scenarios) gigatones of CO₂ (Gt CO₂; 1 Gt = 10¹² kg) (9) will be emitted from the combustion of fossil fuels by existing infrastructure between 2010 and 2060 (Fig. 1, A and B). Adding emissions from non-energy sources, climate model results indicate that these emissions would allow the atmospheric concentration of CO₂ to stabilize below 430 parts per million (ppm), with mean warming of 1.3°C (1.1° to 1.4°C) above the pre-industrial era (or 0.3° to 0.7°C greater than at present; Fig. 1, C and D). Excluding emissions from non-energy sources, atmospheric CO₂ emissions would typically, we answer the following question: What if no additional CO₂-emitting devices (e.g., power plants, motor vehicles) were built, but all the existing CO₂-emitting devices were allowed to live out their normal lifetimes? What CO₂ levels and global mean temperatures would we attain? Of course, the actual lifetime of devices may be strongly influenced by economic and policy constraints. For instance, a ban on new CO₂-emitting devices would create tremendous incentive to prolong the lifetime of existing devices. Thus, our scenarios are not realistic, but they offer a means of gauging the threat of climate change from existing devices relative to those devices that have yet to be built.

The details of our analytic approach are described in (9). In summary, we developed scenarios of global CO₂ emissions from the energy sector (10) using data sets of power plants (11, 12) and motor vehicles (13) worldwide, as well as estimates of fossil fuel emissions produced directly by industry, households, businesses, and other forms of transport (14). We estimated lifetimes and annual emissions of infrastructure from historical data. Non-energy emissions (e.g., from industrial processes, land use change, agriculture, and waste) were taken from the IPCC’s Special Report on Emissions Scenarios (8). We projected changes in CO₂ and temperature in response to our calculated emissions with the use of an intermediate-complexity coupled climate-carbon model, the University of Victoria Earth System Climate Model (9).

Emissions scenarios such as those produced by the Intergovernmental Panel on Climate Change (IPCC) rely on projected changes in population, economic growth, energy demand, and the carbon intensity of energy over time (8). Although these scenarios represent plausible future emissions trends, the infrastructural inertia of emissions at any point in time is not explicitly quantified. Here, we present scenarios reflecting direct emissions from existing energy and transportation infrastructure, along with climate model results showing the warming commitment of these emissions.

With respect to GHG emissions, infrastructural inertia may be thought of as having two important and overlapping components: (i) infrastructure that directly releases GHGs to the atmosphere, and (ii) infrastructure that contributes to the continued production of devices that emit GHGs to the atmosphere. For example, the interstate highway and refueling infrastructure in the United States facilitates continued production of gasoline-powered automobiles. Here, we focus only on the warming commitment from infrastructure that directly releases CO₂ to the atmosphere. Essentially, we answer the following question: What if no additional CO₂-emitting devices (e.g., power plants, motor vehicles) were built, but all the existing CO₂-emitting devices were allowed to live out their normal lifetimes? What CO₂ levels and global mean temperatures would we attain? Of course, the actual lifetime of devices may be strongly influenced by economic and policy constraints. For instance, a ban on new CO₂-emitting devices would create tremendous incentive to prolong the lifetime of existing devices. Thus, our scenarios are not realistic, but they offer a means of gauging the threat of climate change from existing devices relative to those devices that have yet to be built.

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Supporting Online Material
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Materials and Methods
Figs. S1 to S4
References
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1Department of Global Ecology, Carnegie Institution of Washington, 260 Panama Street, Stanford, CA 94305, USA.
2Department of Geography, Planning and Environment, Concordia University, 1455 de Maisonneuve Boulevard West, H 1255-26 (Hall Building), Montreal, Quebec H3G 1M8, Canada.

*To whom correspondence should be addressed. E-mail: sjdavis@stanford.edu

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stabilize below 415 ppm, with mean temperatures 1.2°C (1.1° to 1.3°C) greater than the pre-industrial era. By comparison, scenarios that assume continued expansion of fossil fuel–based infrastructure predict cumulative emissions of 2986 to 7402 Gt CO2 during the remainder of this century (8), leading to warming of 2.4° to 4.6°C by 2100 and atmospheric concentrations of CO2 greater than 600 ppm (15).

We note that 450 ppm and 2°C are climate stabilization benchmarks with substantial currency in international negotiations (16, 17). It is important to recognize that direct emissions from existing infrastructure will not cause these levels to be exceeded. Insofar as the key vulnerabilities of geophysical, biological, and socioeconomic systems manifest themselves beyond these benchmarks (18), the primary threats posed by climate change are a consequence of emissions from devices that do not yet exist.

Of the 1326.7 GW of generating capacity built worldwide since 2000, 416.3 GW (31.4%) are generated from coal, 449.1 GW (33.9%) from natural gas, and 47.5 GW (3.6%) from oil (11) (fig. S1A). Construction of nuclear power plants, the largest source of carbon-free energy, has declined markedly since peaking in the 1980s, constituting only 29.5 GW (2.2%) of generating capacity installed worldwide since 2000 (11). During the same period, other carbon-free energy sources (wind, solar, hydroelectric, geothermal) together account for 231.0 GW (17.4%) of commissioned generating capacity (11).

Historical data from 4573 retired generators indicate that the mean lifetimes of facilities burning coal, natural gas, and oil are 38.6, 35.8, and 33.8 years, respectively [compare with (19)]. It is the combination of these long lifetimes and a predominant share of annual emissions (46.3% in 2007) (14) that results in the largest commitment to future emissions: a cumulative 224 (127 to 336) Gt CO2 from primary energy infrastructure before 2060 (Fig. 1A and table S1).

The transport sector represents the next largest share of annual CO2 emissions (22.9% in 2007) (14). Globalization and rapid economic growth in China and other emerging markets have greatly expanded the global transport sector in the past decade. Moreover, transport infrastructure is fueled almost exclusively by oil, and operating lifetimes can in some cases exceed 30 years. We estimate cumulative committed emissions from transport infrastructure in operation worldwide to be 115 (63 to 132) Gt CO2.

Of the total transport-related emissions, nearly two-thirds is from road transport (74 Gt CO2; Fig. 1A). Although motor vehicle sales in Europe and North America have been steady or slightly declining since 2000, surging vehicle sales in China during the same period reflect growth of private vehicle ownership at a rate of ~20% per year (20). Between 1990 and 2007, the number of motor vehicles in operation worldwide increased by 56% (13), and we estimate the mean age of the global motor vehicle fleet to be 9.7 years (weighted by annual emissions; fig. S1B). Survival rates of late-model vehicles in the United States indicate an average lifetime of 17, 16, and 28 years for passenger cars, light trucks, and heavy vehicles (trucks and buses), respectively. Led by developing economies, emissions from road transport worldwide are projected to continue to grow rapidly over the next several decades (21).

Industrial, residential, and commercial infrastructure that burns fossil fuels also represents a considerable commitment to future emissions.
We estimate the cumulative commitment from industrial equipment to be 104 (61 to 153) Gt CO₂, with residential and commercial infrastructure representing additional emissions of 31 (18 to 47) and 22 (13 to 33) Gt CO₂, respectively (Fig. 1A). Because CO₂-emitting devices in these sectors are generally smaller, more varied, and more numerous than primary energy infrastructure, monitoring of emissions is generally indirect and tied to fuel use. As a result, few data exist on the vintage of existing stocks or expected lifetimes of industrial, residential, and commercial infrastructure. We assume that the vintage and lifetimes are similar to those of primary energy infrastructure, which may overestimate their emissions.

Non-energy emissions, or those unrelated to the combustion of fossil fuels, occur as the result of industrial processes such as the manufacture of cement and steel, where the chemical transformation of feedstocks releases CO₂. Agriculture, waste management, and changing land use also contribute non-energy emissions, as carbon stocks in soils and biomass are oxidized and non-

Fig. 2. (A to C) Regional emissions commitment from existing energy and transportation infrastructure (A), normalized by regional population (B), and normalized by regional GDP (C).
CO₂ greenhouse gases such as N₂O and CH₄ are produced. Although some of these emissions are dictated by infrastructure, this study focuses only on emissions from the energy sector (including transportation). However, it is plausible that under some combination of CCS technologies, reduced conversion of unmanaged land, and changed agricultural and industrial practices, non-energy emissions could diminish in the future. In view of this possibility and to isolate the contributions of existing energy infrastructure and non-energy emissions, we performed simulations including non-energy emissions from a range of scenarios (9) and others in which non-energy emissions were set instantaneously to zero. Excluding non-energy emissions, mean temperatures reach 1.2°C (1.1° to 1.3°C) greater than the pre-industrial era and atmospheric concentrations of CO₂ peak at less than 415 ppm (fig. S2).

Geographically, committed emissions are concentrated in highly developed countries (e.g., western Europe, the United States, Japan) and populous emerging markets in the developing world, particularly China (Figs. 1B and 2A). Infrastructural inertia is greatest in China, where rapid economic development and industrialization in the past decade have led to a prodigious expansion of energy infrastructure. Nearly one-quarter of electrical generating capacity commissioned worldwide since 2000 is in coal-burning plants in China (322.3 GW), and the mean age of power plants operating in China is 12 years (weighted by annual emissions) (11, 12). For these reasons, China alone accounts for roughly 37% of the global emissions commitment: 182 (118 to 244) Gt CO₂ (table S1). Scenarios that included expansion of fossil fuel infrastructure commonly project cumulative emissions from China’s primary energy sector to exceed 300 Gt CO₂ this century [e.g., (20, 22)].

In contrast, committed emissions per unit GDP in both China and India (38.3 and 21.1 kg CO₂ per dollar of GDP, respectively) are much greater than in the most developed countries (e.g., 5.2, 4.5, and 3.8 kg CO₂ per dollar of GDP in the United States, Europe, and Japan, respectively; Fig. 2C), showing that the infrastructural inertia of emissions is greatest where industrialization is under way but incomplete.

Warming and atmospheric CO₂ concentrations from committed emissions were calculated using version 2.9 of the University of Victoria Earth System Climate Model, an intermediate-complexity coupled climate-carbon model (25, 26). We used specified historical CO₂ concentrations to simulate the period from 1750 to 2010. From 2010 to 2100, we specified CO₂ emissions according to our estimates of infrastructural commitments and, in some cases, CO₂ emissions from non-energy sources. Global mean temperatures increase less than 1.4°C in all scenarios, stabilizing when fossil fuel emissions approach zero around mid-century (Fig. 1D). At the upper bound of estimated emissions, the atmospheric concentration of CO₂ peaks in 2046 at 427 ppm (Fig. 1C).

If existing energy infrastructure (e.g., power plants, motor vehicles, furnaces) was used for its normal life span and no new devices were built that emitted CO₂, atmospheric concentrations of CO₂ would peak below 430 ppm and future warming would be less than 0.7°C. However, there is little doubt that more CO₂-emitting devices will be built. Our analysis considers only devices that emit CO₂ directly. Substantial infrastructure also exists to produce and facilitate use of these devices. For example, factories that produce internal combustion engines, highway networks dotted with gasoline refueling stations, and oil refineries all promote the continuation of oil-based road transport emissions. Moreover, satisfying growing demand for energy without producing CO₂ emissions will require truly extraordinary development and deployment of carbon-free sources of energy, perhaps 30 TW by 2050 (27, 28). Yet avoiding key impacts of climate change depends on the success of efforts to overcome infrastructural inertia and commission a new generation of devices that can provide energy and transport services without releasing CO₂ to the atmosphere.

References and Notes

9. See supporting material on Science Online.
10. Includes all CO₂ emissions under category IA of the IPCC Guidelines for National Greenhouse Gas Emissions: fuel combustion by commercial power plants, industry, transport, commercial, and households.
12. CARMA Database v. 2.0 (http://carma.org/).
23. Results reported for “European” countries represent the 27 EU member countries. The mean age of European infrastructure is the emissions-weighted average of these countries.
29. We thank M. Hoffman of the Center for Global Development for help linking the CARMA and Platt’s power plant databases (J1, 12).

Supporting Online Material

www.sciencemag.org/cgi/content/full/329/5997/1330/DC1 Materials and Methods
Figures S1 to S3
Tables S1 and S2
References

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Editor's Summary

What We're In For

What would our climate future look like if we stopped building any new infrastructure that used fossil fuels? Davis et al. (p. 1330; see the Perspective by Hoffert) made the assumption that all existing infrastructure will be used until the end of its lifetime, after which it will be replaced by infrastructure that does not produce CO$_2$. They then calculated the amount of additional CO$_2$ that will be added to the atmosphere. The outcome is that the concentration of atmospheric CO$_2$ would remain below 430 parts per million (ppm) (present levels are 390 ppm) and global mean temperatures would increase to 1.3°C above preindustrial values (about 0.5°C above present), well below current targets of 450 ppm and 2°C, respectively.

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