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38. This work was supported by grants from Cbana Laboratories and Dioxide Materials. C.R.F. developed the sensor fabrication method that allowed the measurements to be made. K.Y.L. took most of the data. A.S.-K. directed much of the data acquisition and worked with R.I.M. to understand how Poole-Frenkel conduction would affect nanotube sensor response. R.I.M. wondered if current stimulated could occur and asked A.S.-K. to devise experiments to see if it did occur. R.I.M. and A.S.-K. drafted the paper. The authors are submitting patents based on some aspects of the work.

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Future CO_2 Emissions and Climate Change from Existing Energy Infrastructure

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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) gigatonnes of CO_2 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 and atmospheric concentrations of CO_2 less than 430 parts per million. Because these conditions would likely avoid many key impacts of climate change, we conclude that sources of the most threatening emissions have yet to be built. However, CO_2-emitting infrastructure will expand unless extraordinary efforts are undertaken to develop alternatives.

If current greenhouse gas (GHG) concentrations remain constant, the world would be committed to several centuries of increasing global mean temperatures and sea level rise (*1–3*). By contrast, near-elimination of anthropogenic CO_2 emissions would be required to produce diminishing GHG concentrations consistent with stabilization of mean temperatures (*4–6*). Yet long-lived energy and transportation infrastructure now operating can be expected to contribute substantial CO_2 emissions over the next 50 years [e.g., (*7*)]. Barring widespread retrofitting of existing power plants with carbon capture and storage (CCS) technologies or the early decommissioning of serviceable infrastructure, these "committed emissions" represent infrastructural inertia, which may be the primary contributor to total future warming commitment.

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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 CO_2 to the atmosphere. Essentially, we answer the following question: What if no additional CO_2-emitting devices (e.g., power plants, motor vehicles) were built, but all the existing CO_2-emitting devices were allowed to live out their normal lifetimes? What CO_2 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 CO_2-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 CO_2 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 CO_2 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*).

Cumulatively, we estimate that 496 (282 to 701 in lower- and upper-bounding scenarios) gigatonnes of CO_2 (Gt CO_2; 1 Gt = 10^{12} 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 CO_2 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 CO_2 emissions would 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 CO_2 during the remainder of this century (*8*), leading to warming of 2.4° to 4.6°C by 2100 and atmospheric concentrations of CO_2 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 CO_2 from primary energy infrastructure before 2060 (Fig. 1A and table S1).

The transport sector represents the next largest share of annual CO_2 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 CO_2.

Of the total transport-related emissions, nearly two-thirds is from road transport (74 Gt CO_2; 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.

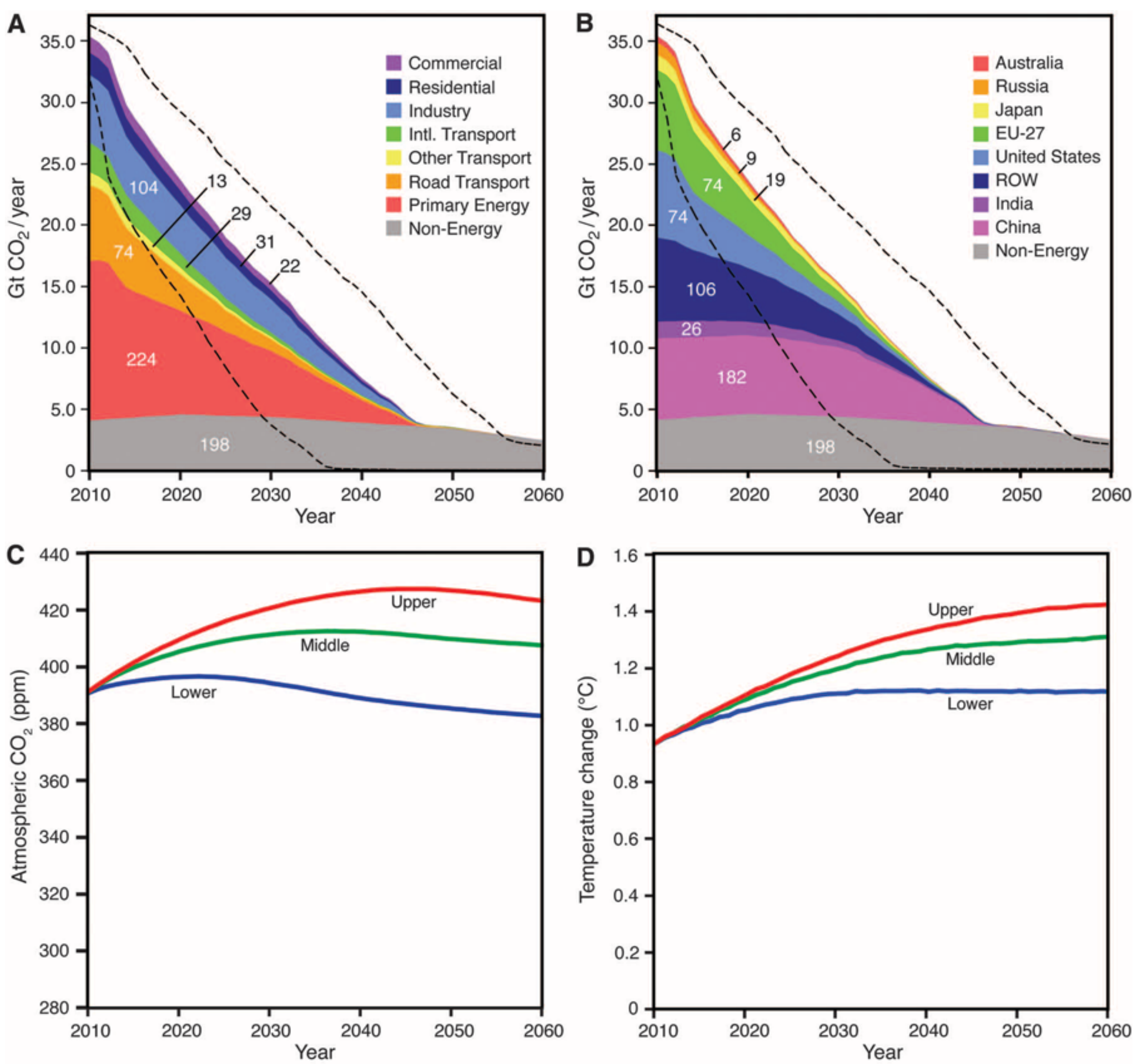

Fig. 1. (**A** to **D**) Scenario of CO_2 emissions from existing energy and transportation infrastructure by industry sector (A) and country/region (B), as well as response of atmospheric CO_2 (C) and global mean temperature (D). In (A) and (B), the non-energy emissions shown are global emissions projected under the IPCC Special Report on Emission Scenarios A2 marker scenario, and dashed lines indicate total emissions from upper- and lower-bounding scenarios. Vertical axis for all panels indicates change from pre-industrial values.

We estimate the cumulative commitment from industrial equipment to be 104 (61 to 153) Gt CO_2, with residential and commercial infrastructure representing additional emissions of 31 (18 to 47) and 22 (13 to 33) Gt CO_2, respectively (Fig. 1A). Because CO_2-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 CO_2. Agriculture, waste management, and changing land use also contribute non-energy emissions, as carbon stocks in soils and biomass are oxidized and non-

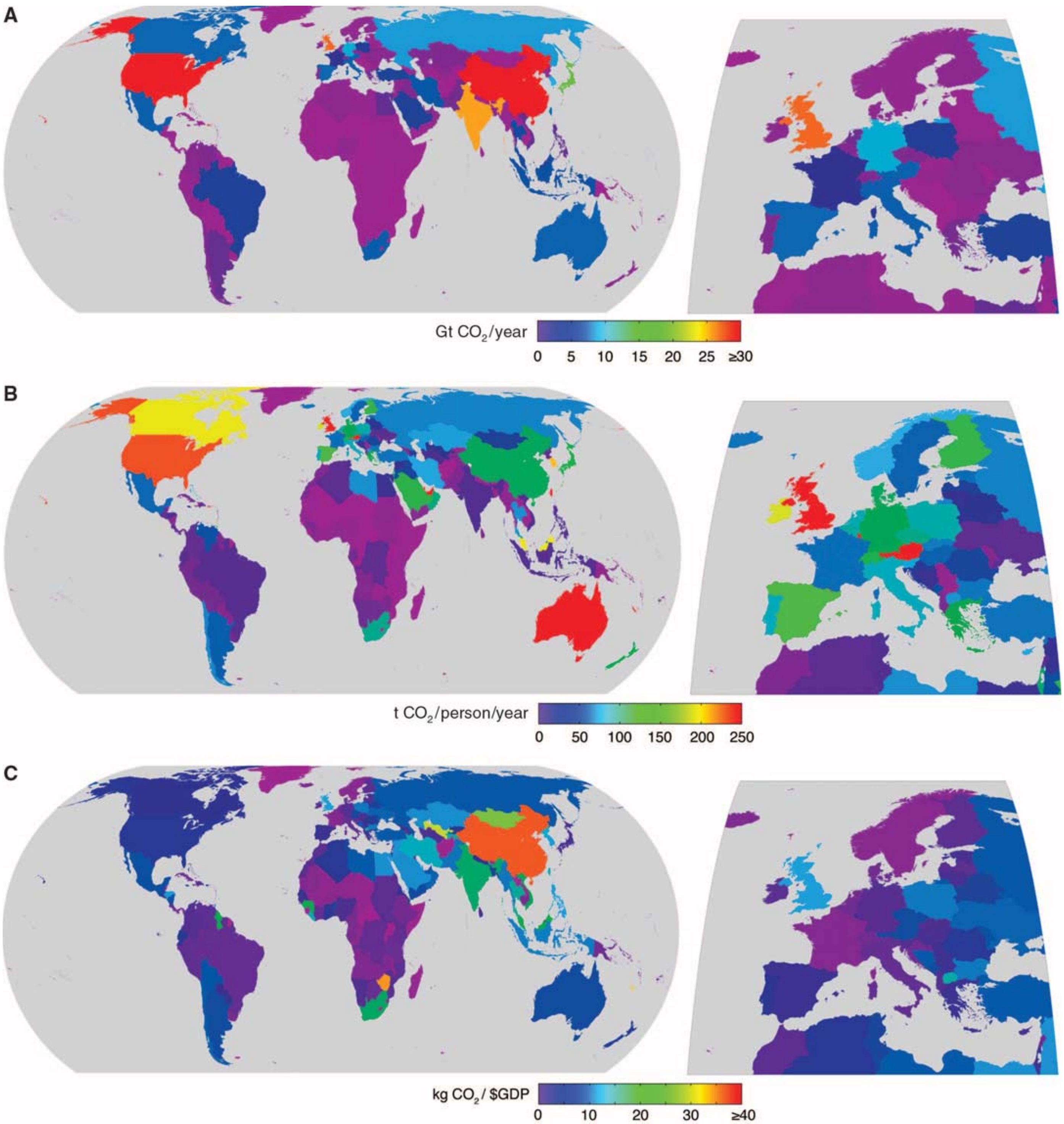

Fig. 2. (**A** to **C**) Regional emissions commitment from existing energy and transportation infrastructure (A), normalized by regional population (B), and normalized by regional GDP (C).

CO_2 greenhouse gases such as N_2O and CH_4 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 CO_2 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 CO_2 (table S1). Scenarios that allow continued expansion of fossil fuel infrastructure commonly project cumulative emissions from China's primary energy sector to exceed 300 Gt CO_2 this century [e.g., (*20*, *22*)].

In comparison, the mean age of power plants in the United States is 32 years, and generating capacity added since 2000 is predominantly gas-fired (187.6 GW) and wind-generated (28.3 GW), with coal a distant third (8.0 GW). The mean age of Japanese and European power plants is similarly advanced: 21 and 27 years, respectively (*23*). Thus, although current CO_2 emissions from China and the United States are similar in magnitude, the infrastructural commitment to future CO_2 emissions is much greater in China, because China's energy infrastructure is younger than that of the United States, and thus has a longer remaining lifetime. Nonetheless, infrastructure in the United States, Europe, and Japan represents cumulative commitments of 74, 74, and 19 Gt CO_2, representing 15%, 15%, and 4% of the global emissions commitment, respectively (Fig. 1B).

Emissions commitments per capita and per unit GDP are important indicators of global equity that further highlight the uneven distribution of energy services between developed and developing regions (Fig. 2, B and C, and table S2). Despite its much larger population, emissions commitment per capita in China (136 t CO_2 per person) is remarkably similar to that in Japan and Europe (152 and 150 t CO_2 per person, respectively), but still considerably less than the commitment of 241 t CO_2 per person in the United States (Fig. 2B). The comparability of per capita commitments in China and the most developed countries underscores the global importance of future emissions and climate policy in China, but ignores the legacy of historical emissions as well as the role of consumption in developed countries in driving Chinese emissions (*24*). Elsewhere, greater inequities persist: The per capita commitment in India of only 23 t CO_2 per person means that each individual in China and the United States is committed to the same emissions as ~6 and ~10 individuals in India, respectively.

In contrast, committed emissions per unit GDP in both China and India (38.3 and 21.1 kg CO_2 per dollar of GDP, respectively) are much greater than in the most developed countries (e.g., 5.2, 4.5, and 3.8 kg CO_2 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 CO_2 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 CO_2 concentrations to simulate the period from 1750 to 2010. From 2010 to 2100, we specified CO_2 emissions according to our estimates of infrastructural commitments and, in some cases, CO_2 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 CO_2 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 CO_2, atmospheric concentrations of CO_2 would peak below 430 ppm and future warming would be less than 0.7°C. However, there is little doubt that more CO_2-emitting devices will be built. Our analysis considers only devices that emit CO_2 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 CO_2 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 CO_2 to the atmosphere.

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Supporting Online Material

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References

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