into a macroscopic electrical network. Thus, electrical connections from the macroscopic scale to individual SWNTs can now be easily made via the micrometre-scale islands. Using this approach, we have designed and fabricated individual SWNT electrical circuits by direct CVD syntheses on insulating SiO_2 substrates with the patterned catalyst islands connected to macroscopic metal electrodes (see Supplementary Information). By mechanical manipulation of nanotube bridges using contact mode AFM[12], we have obtained evidence of strong mechanical fixation of nanotubes to the islands. Further, we have measured the lateral forces needed to break individual SWNTs and estimated the tensile strength of SWNTs (of the order of 200 GPa; see Supplementary Information).

We have chosen methane for carbon feedstock in our CVD synthesis because methane is the most kinetically stable hydrocarbon at elevated temperatures. Previously, extensive work has been done using methane in catalysed CVD synthesis of carbon fibres at temperatures up to 1,100 °C (refs 13–16). At 1,000 °C, the catalytic decomposition of methane by our catalyst dominates over self-pyrolysis, at least within a timescale of 10 min. This is evident from our observation that no obvious amorphous carbon coating exists on the side walls of the nanotubes. However, an amorphous carbon coating can build up over time. Previous work on micrometre-scale carbon-fibre synthesis showed that as the reaction is allowed to take place for hours, methane pyrolysis at ~1,000 °C leads to an appreciable thickness of carbon coating over a nanotube core[13–16]. By limiting our CVD synthesis to 10 min and using a relatively high flow rate, we are able to avoid the amorphous carbon coating.

To confirm that the methane CVD approach produces individual SWNTs, we prepared bulk catalyst supported on alumina nanoparticles. The catalyst preparation involves impregnation of 4.0 g alumina nanoparticles with 1.0 g $Fe(NO_3)_3{\cdot}9H_2O$ in 30 ml methanol for 24 h, after which the methanol is removed by evaporation at 80 °C. Using this bulk catalyst, we carried out methane CVD under exactly the same conditions as with the patterned Si substrates. Using a transmission electron microscope (TEM), we found abundant SWNTs (see Fig. 4 and ref. 17). The diameter range of the individual SWNTs was 1–5 nm, with a mean of 1–2 nm. Ends of SWNTs were frequently observed under TEM. All of the ends imaged so far appear to be closed and free of metal particles (Fig. 4, inset). From these observations, we infer that the SWNTs grow in methane CVD by a 'base-growth' mechanism. Base growth and tip growth are the two mechanisms that have been proposed for CVD growth of various forms of carbon tubes[18–21]. The first step of such a CVD process involves the absorption and decomposition of hydrocarbon molecules on the surface of a transition metal (Fe, Ni, Co, for example) catalyst, followed by diffusion of carbon atoms into the catalyst bulk from the supersaturated surface[19–21]. The tip-growth model involves a metal catalyst particle at a nanotube end being carried away as the nanotube lengthens: thus, the carried-along particle is responsible for supplying carbon feedstock needed for the nanotube growth. In contrast, base growth involves a nanotube lengthening with a particle-free closed end. Carbon feedstock is supplied from the base where the nanotube interfaces with the catalyst material. In our methane CVD system, because there are only closed particle-free nanotube ends we conclude that the base-growth mechanism operates under our conditions. For SWNT syntheses on patterned substrates, we are effectively making catalyst *in situ* in PMMA-defined Petri dishes (Fig. 1). Our synthetic strategy should allow rational design of various single-walled nanotube devices by direct chemical synthesis. □

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Energy implications of future stabilization of atmospheric CO_2 content

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The United Nations Framework Convention on Climate Change[1] calls for "stabilization of greenhouse-gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system . . .". A standard baseline scenario[2,3] that assumes no policy intervention to limit greenhouse-gas emissions has 10 TW (10×10^{12} watts) of carbon-emission-free power being produced by the year 2050, equivalent to the power provided by all today's energy sources combined. Here we employ a carbon-cycle/energy model to

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estimate the carbon-emission-free power needed for various atmospheric CO_2 stabilization scenarios. We find that CO_2 stabilization with continued economic growth will require innovative, cost-effective and carbon-emission-free technologies that can provide additional tens of terawatts of primary power in the coming decades, and certainly by the middle of the twenty-first century, even with sustained improvement in the economic productivity of primary energy. At progressively lower atmospheric CO_2-stabilization targets in the 750–350 p.p.m.v. range, implementing stabilization will become even more challenging because of the increasing demand for carbon-emission-free power. The magnitude of the implied infrastructure transition suggests the need for massive investments in innovative energy research.

Intergovernmental Panel on Climate Change (IPCC) working groups developed six scenarios for greenhouse-gas emissions based on socioeconomic projections[2,3]. Scenario IS92a incorporated widely accepted projections and the then-current consensus on population, economic development and energy technology to generate projections of greenhouse-gas emissions for the twenty-first century assuming "no new climate change policies". This baseline IS92a scenario has been dubbed 'business as usual'.

In general, the rate at which carbon is emitted (as CO_2) by energy production is given by the Kaya identity[4–6];

$$\dot{M}_c \equiv N(\mathrm{GDP}/N)(\dot{E}/\mathrm{GDP})(C/E) \qquad (1)$$

expressing emissions as the product of population (N), per capita gross domestic product (GDP/N), primary energy intensity ($\dot{E}$/GDP) and carbon intensity (C/E). Here we express the rate of primary energy consumption from all fuel sources (the "burn rate") in watts (W) and the gross domestic product in (1990 US) \$ yr^{-1} so their ratio, the energy intensity, has units of W yr \$$^{-1}$. Carbon intensity, the weighted average of the carbon-to-energy emission factors of all energy sources, has the units kg C W^{-1} yr^{-1}. For example, from equation (1) fossil-fuel CO_2 emissions in 1990 were $\dot{M}_c = 5.3 \times 10^9$ persons $\times$ 4,100 \$ per person yr^{-1} $\times$ 0.49 W yr \$$^{-1}$ $\times$ 0.56 kg C W^{-1} yr^{-1} $\approx$ 6.0 Gt C yr^{-1} (1 Gt C $= 10^{12}$ kg C).

To illustrate the relative contributions of the factors in equation (1) historically and under IS92a, we evaluated each of them globally over the 210-year period from 1890 to 2100 (Fig. 1) from historical data[7–9] before 1990, and from documents defining IPCC scenarios[2,10–12] after 1990. Although some of this information is implicit in IPCC documents, it has not been previously presented in this way.

Although illustrating the 'big picture', aggregating Kaya decomposition terms globally can mask regional developmental differences[13]. Data for individual nations indicate that $\dot{E}$/GDP typically increases during economic development, reaching a maximum as infrastructure investments peak, and declining only after some lag as economic productivity rises and the economy shifts structurally to less-energy-intensive activities (for example,

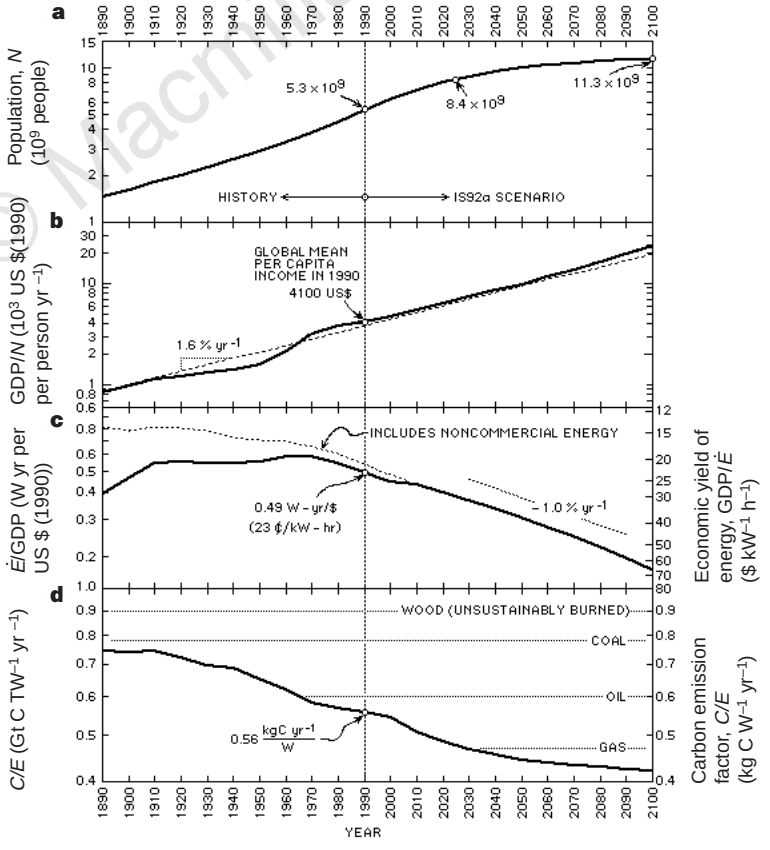

Figure 1 Evolution of factors governing the rate of global fossil-fuel carbon emissions in the Kaya identity: $\dot{M}_c \equiv N(\mathrm{GDP}/N)(\dot{E}/\mathrm{GDP})(C/E)$. Historical curves (1890–1990) are from archival data[7–9]; future projections (1990–2100) are computed for the IPCC IS92a scenario[2,10–12]. GDP is inflation-corrected to 1990 US dollars. **a**, Global population; **b**, Per capita GDP; **c**, primary energy intensity ($\dot{E}$/GDP: left hand scale) and economic productivity of energy (GDP/$\dot{E}$: right hand scale); **d**, carbon intensity of the energy mix; the horizontal lines are emission factors of individual carbonaceous fuels. Global population, N, shown after 1990 is the *UN* mid-range projection made at the time the IS92 scenarios were developed. It reaches 11.3 billion by 2100. Per capita global mean GDP continues its monotonic rise at ~1.6% yr^{-1} over the entire twenty-first century. The primary energy intensity incorporates both engineering energy efficiency and structural changes in the economy governing the material content of economic growth.

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services)[14]. Apparently declining, energy intensities of India and China today are still 2 to 5 times the global mean[8]. To focus on energy supply issues we provisionally accept the IS92a projections of 1% yr^{-1} improvement in global $\dot{E}$/GDP, recognizing that achieving this will depend crucially on the technology and structural changes adopted by developing nations[15].

Another opportunity for emission reductions is continuation of the "decarbonization" of the past 100 years reflected in decreasing carbon intensity of the global energy mix[8]. Under IS92a, the global mean *C/E* continues to decrease monotonically over the next century (Fig. 1d). Indeed, the evolving global energy mix based on assumed declining costs of nuclear and carbon-free energy relative to fossil fuels has global *C/E* dropping to that of natural gas by 2030; and it declines even more thereafter. Such rapid decarbonization is possible only by the massive introduction of carbon-free power, ~10 TW by 2050. Even with this much carbon-free power and sustained 1% yr^{-1} improvements in energy intensity, the net effect of the factors in equation (1) more than doubles 1990 CO_2 emissions by 2050.

Figure 2 shows carbon emissions (Fig. 2a), primary power levels (Fig. 2b) and carbon-free primary power (Fig. 2c) required over the twenty-first century for IS92a and CO_2 stabilization scenarios. Even the optimistic decline of the last two factors in the Kaya identity cannot prevent emissions from increasing from 6 Gt C yr^{-1} in 1990 to ~20 Gt C yr^{-1} by 2100 under 'business as usual' (Fig. 2a). Also shown as differently shaded zones are the relative contributions of natural gas, oil and coal to emissions. A feature of IS92a worth noting is that the share of carbon-intensive coal, relative to less-carbon-intensive natural gas and oil, rises after 2025, but the carbon intensity (*C/E*) of the fuel mix declines overall, a feature possible only by the massive introduction of carbon-free energy sources.

The curves in Fig. 2a are allowable emission levels over time which ultimate stabilize atmospheric CO_2 at 750, 650, 550, 450 and 350 p.p.m.v. computed for the Wigley, Richels and Edmonds stabilization paths[16,17]. These delayed stabilization paths, which follow IS92a emissions early on, with large reductions later (hereafter, WRE 350, 450,..., 750 scenarios), could buy time to attain CO_2 stabilization goals. This is possible because a given atmospheric CO_2 concentration goal depends roughly on cumulative carbon emissions and can be approached by an infinite number of paths, some of which constrain emissions early, some later. However, Wigley, Richels and Edmonds did not consider whether their paths were a realistic transition from the present fossil-fuel system. They emphasized that their "results should not be interpreted as a 'do nothing' or 'wait and see' policy", calling for prompt and sustained commitment to research, development and demonstration to ensure that low-carbon and carbon-free energy alternatives are available when needed[16].

The black topmost curve in Fig. 2b shows the evolution of total primary power required to meet the economic goals of IS92a, with gas, oil, coal, nuclear and renewable components shown as coloured areas. Also shown are allowable primary power levels from fossil-fuel sources computed for WRE stabilization scenarios. The difference between the IS92a total primary power, $\dot{E}$, and fossil-fuel power allowable for CO_2 stabilization, $\dot{E}_f$, must be provided by carbon-free sources if the economic and "efficiency" assumptions of IPCC 'business as usual' are maintained; an increasingly challenging goal as the CO_2 concentration target is lowered.

Figure 2c shows carbon-free power, $\dot{E}_{cf} = \dot{E} - \dot{E}_f$, required for IS92a and for CO_2 stabilization via WRE 350–750 paths in a world

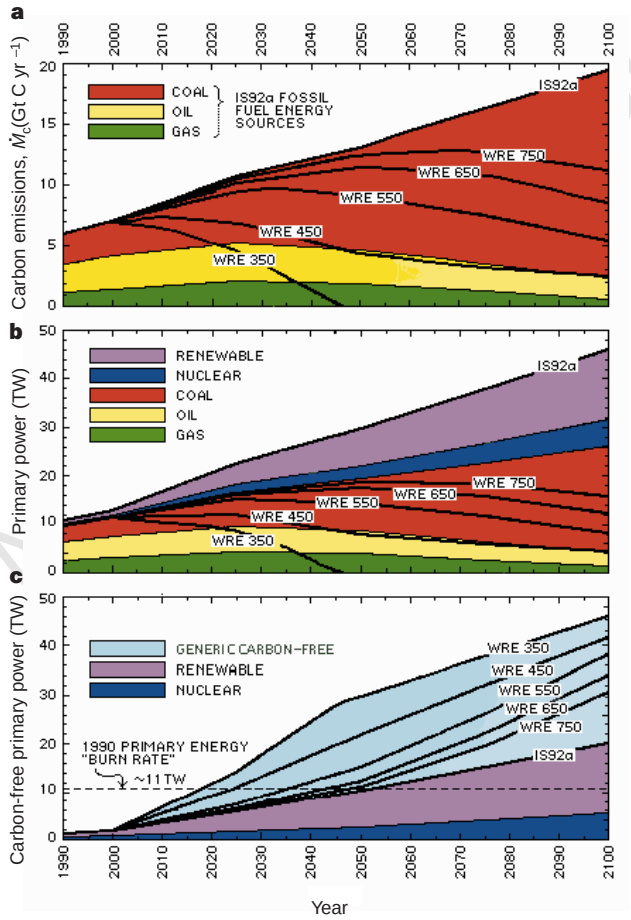

Figure 2 Fossil-fuel carbon emissions and primary power in the twenty-first century for IPCC IS92a and WRE stabilization scenarios. **a**, Carbon emissions; **b**, primary power and **c**, carbon-free primary power. Coloured areas are gas, oil, coal, nuclear and renewable components of IS92a from the energy economics model of Pepper *et al.*[12]. Carbon emissions for WRE scenarios[16] are outputs of our inverse carbon-cycle model[17]. Fossil-fuel power for WRE scenarios is based on IS92a burn rates of gas, oil and coal employed sequentially in descending priority, and limited by total carbon emission caps. Carbon-free primary power is total primary power less fossil-fuel carbon power.

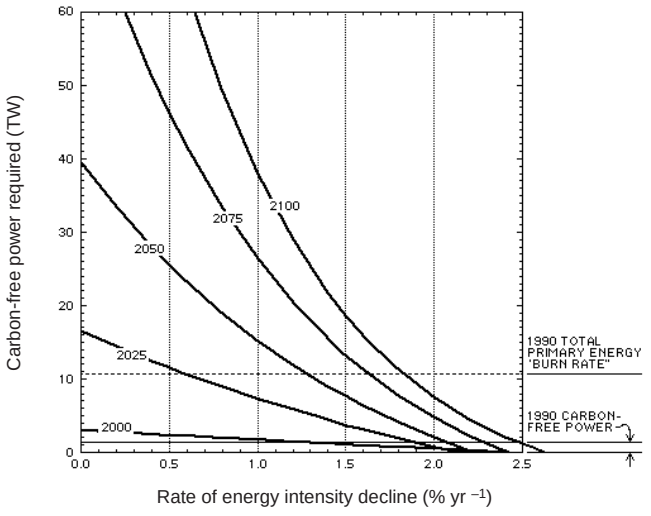

Figure 3 Twenty-first century trade-offs, between carbon-free power required and "energy efficiency", to stabilize at twice the pre-industrial CO_2 concentration. Carbon-free primary power is plotted versus the annual rate of decline in energy intensity. The latter is defined as $-[d(\dot{E}/GDP)/dt](\dot{E}/GDP)^{-1}100\%$. All cases assume WRE 550 CO_2 stabilization paths and GDP growth of 2.9% yr^{-1} to 2025, 2.3% yr^{-1} thereafter. The rate of energy intensity decline in IS92a and in our CO_2 stabilization base cases is ~1.0% yr^{-1}.

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economy growing as IS92a and with the same improvement rate in $\dot{E}$/GDP. In that case stabilizing CO_2 concentrations at 1990 levels according to WRE 350 will require ~10 TW of carbon-free primary power by 2018, equal to the total 1990 primary power of the world economy. WRE 550, which leads to an approximate doubling of pre-industrial atmospheric CO_2, requires this much carbon-free power by 2035. These results imply a massive transition from the present fossil-fuel-dominated energy infrastructure to carbon-free sources in the coming decades to stabilize CO_2 at reasonable target values. Even IS92a requires ~10 TW carbon-free power by 2050.

Studies by US DOE laboratories in support of the Kyoto negotiations to reduce carbon emissions in the 1998–2010 time frame emhasize demand side reductions from improved energy efficiency in motor vehicles, buildings and electrical appliances[18]. Our analysis indicates that beyond 2010 new carbon-free primary power technologies will increasingly be needed even with significant improvements in the ability to convert primary power into GDP.

Figure 3 shows the trade-off between increases in carbon-free power and energy efficiency improvements, expressed as the annual percentage improvement in $\dot{E}$/GDP required to achieve a 2 × pre-industrial CO_2 goal by the WRE 550 path. Sustained improvement of energy intensity of order $\pm 1.0\%\,yr^{-1}$ relative to the base case ($1\%\,yr^{-1}$) creates increasingly large differences in carbon-free power required as the twenty-first century progresses (Fig. 3). For a $2\%\,yr^{-1}$ compounded growth, the carbon-free power required remains modest even by the year 2100. But $2\%\,yr^{-1}$ may be almost impossible to sustain over the next century, as that would imply growing the world population and economy significantly at nearly constant primary power. If there is no improvement in energy intensity, some 40 carbon-free terawatts could be needed by 2050.

The authors of the IPCC central 'business as usual' scenario (IS92a) believed that an exponential decline in $\dot{E}$/GDP of $1\%\,yr^{-1}$ would be sustainable over the next century employing only those emission-control policies internationally agreed to at the 1992 Rio climate treaty negotiations[1,2]. But either deploying 10–30 TW carbon-free power or improving $\dot{E}$/GDP by $2\%\,yr^{-1}$ will be very difficult. The need to push hard on both improving energy supply and reducing demand is demonstrated by our analysis, as well as the fact that there are real trade-offs—more of one can significantly diminish the need for the other.

Stabilizing atmospheric CO_2 at twice pre-industrial levels while meeting the economic assumptions of 'business as usual' implies a massive transition to carbon-free power, particular in developing nations. There are no energy systems technologically ready at present to produce the required amounts of carbon-free power[6]. Some suggest the answer may be integrated energy systems based on fossil fuels[19] in which carbon dioxide[20] or solid carbon[21] is sequestered in reservoirs isolated from the atmosphere, or "geoengineering" compensatory climate changes[22–24]. Despite potentially serious environmental and cost problems, these approaches would allow fossil fuel, increasingly coal, to continue its historic rise as the primary energy source of the next century.

It is time now to look hard at the engineering feasibility of transformative technologies that can change the way primary energy itself is produced. It is within the range of climate change and impact projections that stabilization of atmospheric CO_2 at some level below the IS92a baseline is necessary to mitigate large adverse effects on global economies and ecosystems[3]. In that case, a massive infusion of new energy-producing technologies at the required scale could be needed to prevent "dangerous anthropogenic interference with the climate system" (ref. 1).

Analyses of carbon emissions targets thus far have quite reasonably emphasized market economics theory. Some suggest that market forces alone, perhaps supplemented by carbon taxes, are sufficient to stimulate adequate levels of innovation in emission-reducing technologies. However, market inefficiencies may preclude timely development of such technologies at the required scale[25]. There are renewable[26,27], fission[28] and fusion[29] concepts incorporating innovative technological ideas at early research and development stages that could, in principle, provide the needed carbon-free power. But without policy incentives to overcome socioeconomic inertia these could take more than 50 years to penetrate to their market potential[30].

These results underscore the pitfalls of 'wait-and-see'. This past century, accelerated technology development from wartime and postwar research produced commercial aviation, radar, computer chips, lasers and the Internet, among other things. Researching, developing and commercializing carbon-free primary power technologies capable of 10–30 TW by the mid-twenty-first century could require efforts, perhaps international, pursued with the urgency of the Manhattan Project or the Apollo space programme. The roles of governments and market entrepreneurs in the eventual deployment of such technologies need to be considered more comprehensively than we can do here. But the potentially adverse effect of humanity on the Earth's climate could well stimulate new industries in the twenty-first century, as did the Second World War and the 'cold war' in this century. □

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