Energy and Health 6

Policies for accelerating access to clean energy, improving health, advancing development, and mitigating climate change

Andy Haines, Kirk R Smith, Dennis Anderson, Paul R Epstein, Anthony J McMichael, Ian Roberts, Paul Wilkinson, James Woodcock, Jeremy Woods

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This is the sixth in a Series of six papers about energy and health

London School of Hygiene and Tropical Medicine, London, UK (Prof A Haines F Med Sci, Prof I Roberts PhD, P Wilkinson FRCP, J Woodcock MSc); **University of California, Berkeley, Berkeley, CA, USA** (Prof K R Smith PhD); **Imperial College London, London, UK** (Prof D Anderson MSc, J Woods PhD); **Harvard Medical School, Boston, MA, USA** (P R Epstein MD); **and Australian National University, Canberra, ACT, Australia** (Prof A J McMichael PhD)

The absence of reliable access to clean energy and the services it provides imposes a large disease burden on low-income populations and impedes prospects for development. Furthermore, current patterns of fossil-fuel use cause substantial ill-health from air pollution and occupational hazards. Impending climate change, mainly driven by energy use, now also threatens health. Policies to promote access to non-polluting and sustainable sources of energy have great potential both to improve public health and to mitigate (prevent) climate disruption. There are several technological options, policy levers, and economic instruments for sectors such as power generation, transport, agriculture, and the built environment. However, barriers to change include vested interests, political inertia, inability to take meaningful action, profound global inequalities, weak technology-transfer mechanisms, and knowledge gaps that must be addressed to transform global markets. The need for policies that prevent dangerous anthropogenic interference with the climate while addressing the energy needs of disadvantaged people is a central challenge of the current era. A comprehensive programme for clean energy should optimise mitigation and, simultaneously, adaption to climate change while maximising co-benefits for health—eg, through improved air, water, and food quality. Intersectoral research and concerted action, both nationally and internationally, will be required.

Links between energy use and public health

Previous articles in this Series have described the public-health implications of fuel combustion, power generation, livestock production and consumption, and patterns of energy use. Although there is a range of important health effects, including those associated with occupational safety and health in energy industries, the low-probability/high-consequence accident risks from nuclear and hydroelectric facilities, the diverse health risks from global climate change, and the association of high-energy-use lifestyles with obesity, two major sources of disease burden today from energy use are indoor and outdoor air pollution.[1]

Key messages

- Increased access to clean energy services for poorest populations of world is current high priority for public health
- Reducing public-health effects of current fossil fuel use is also a priority
- With careful planning, appropriate incentives, and development and spread of advanced technologies, these goals can be met in ways that also help to reduce risk of climate change, the biggest long-term challenge in relation to energy use
- Society needs to find ways to limit global warming to around 2°C, thereby reducing the risk of most serious consequences of climate change. Policies to achieve this should be political priority, especially in industrialised countries
- The needed transformations in patterns of power generation and energy use are very great (eg, around 90% reduction in carbon dioxide emissions in UK), and they will require major policy initiatives and legal, fiscal, economic, and other measures to achieve. Policies to reduce human population growth and livestock production could also have an important role in reducing greenhouse-gas emissions
- There are imperatives to transfer technology to less developed countries to ensure their urgent health and development needs can be met without further contributing to adverse health and environmental effects at local and global levels
- The challenge faced by society in moving to cleaner, healthier, more sustainable patterns of energy use is comparable to great public-health challenges of earlier generations, and its successful achievement will require bold and visionary leadership, which we predict would result in substantial benefits to global health both in the short and long terms

One of the major neglected challenges to public health is the lack of access to clean and reliable energy and energy services on the part of the nearly 2·4 billion people who depend on traditional biomass for cooking and the 1·6 billion that do not have access to electricity.[2] Lack of access to clean energy currently has major effects on public health through, in particular, the disease burden arising from exposure to high levels of indoor air pollution largely in low-income countries (attributable annual mortality of about 1·6 million). Household coal use in China poses especially high health risks, particularly in those many areas where highly polluting, toxin-containing coals are used. Historically, households have moved to cleaner fuels as economic development progresses, but this process would not by itself substantially reduce the global health risks for many decades. Additionally, with what seems to be the inexorable rise in oil prices, the ability of poor households to move to cleaner fuels—eg, kerosene and liquified petroleum gas—is being delayed and perhaps even denied to these populations. Concerted intervention is needed.

The effect of urban air pollution on health in cities with populations over 100 000, which is largely due to fossil fuel combustion, is also substantial (attributable annual mortality about 0·8 million).[3] The burden of outdoor air pollution in smaller cities and rural areas, which is not well characterised but affects an even larger population, would increase this toll even further. With steady urbanisation, particularly in India and China where coal remains the chief fuel used and vehicle fleets are growing at historically unprecedented rates, there is a real possibility that the total health burden could actually rise unless more stringent control actions are taken.

At the same time, the world faces an unprecedented challenge from anthropogenic (ie, human induced) climate change, largely due to the unrestrained use of fossil fuels by industrialised countries, resulting in the accumulation of greenhouse gases (mainly carbon dioxide but also methane, nitrous oxide, ozone, hydrochlorofluorocarbons, and hydrofluorocarbons) in the atmosphere. The growing evidence about the speed and magnitude of climate change is forcing decision-makers to consider policy options that prevent the further accumulation of greenhouse gases. The potential public-health effects of climate change have been discussed elsewhere.[4,5] In summary, climate change could affect public health through a range of pathways, including effects on food yields, deaths related to heat and cold, extreme events such as floods, droughts, and wind storms, and shifts in the ranges of infectious diseases and disease vectors and in the intensity of outbreaks. The public-health effects of climate change are therefore likely to be adverse on balance, and to disproportionately affect poor populations in tropical and sub-tropical regions. However, the European heat wave of 2003 and Hurricane Katrina showed that the populations of rich nations (albeit particularly disadvantaged groups within those countries) can also experience major adverse effects from extreme climatic events that are likely to increase in frequency and intensity with climate change.[6,7]

Moreover, climate change, together with widespread change in land use, decline of marine ecosystems, loss of biodiversity, depletion of fresh water, and continuing population growth, threatens the life-support systems that underpin public health.[8] The attendant uncertainties about the full range of effects resulting from climate change and from interactions between these complex processes should not be an excuse for inaction, especially as there are many policies that can improve health and mitigate climate change.

The Stern review[9] of the economic effects of climate change estimated that the cost of near-term action to mitigate climate change is likely to be substantially less than would be the subsequent cost of inaction. The effects of climate change could result in losing around 5% of gross world product (GWP) by the middle of the 21st century, perhaps even reaching 20% or more if the full range of potential health, ecological, and economic effects is considered. To the extent that the loss of income growth would differentially affect poor people, the economic effects themselves would affect public health.

In the absence of decisive action to curb greenhouse-gas emissions, their concentrations could reach twice pre-industrial levels as early as 2035, leading to a probable globally averaged temperature increase of 2°C or more. Even more worryingly, under a business-as-usual scenario, there is a 50% probability of temperatures increasing by 5°C in the early decades of the next century, with potentially wide-ranging harmful consequences.

Policies to promote access to non-polluting and sustainable sources of energy therefore have great potential to improve public health in the near term as well as mitigating further climate change.[10,11] Positive effects such as these are often referred to as co-benefits of mitigation policies on climate change. Provision of adequate energy supplies could also help reduce the vulnerability of poor populations to the effects of climate change by underpinning human development. Actions that focus on both short-term improvements—eg, in health—as well as limiting long-term risks from climate change are often termed “no regrets”, in that they will be beneficial even if climate change risks turn out to be less than now feared.

Here, we build on the previous articles in the Series and consider the factors that affect the greenhouse-gas emissions from various sectors. We summarise the policy options for addressing the lack of access to clean and reliable supplies of energy and the services that arise from their use, while mitigating climate change through a range of sectoral policies that reduce greenhouse-gas emissions on a global scale. However, without radical change, such emissions will continue to climb inexorably. Indeed, on current trends, fossil fuels are projected to cater for 90% of the increased energy demand—which will grow by 1·7% per year—until 2030.[12]

Technologies and practices for greenhouse-gas mitigation

There is no shortage of technological options and practices that would enable the world to enjoy the benefits of using energy while moving to an energy system with low emissions of greenhouse gases. The world’s energy needs could eventually be met several times over by such energy resources, and through improving efficiency in energy consumption and use. Surveys are provided elsewhere;[13–19] the key options are summarised in the panel.

Energy efficiency improvements are nearly always the easiest, cheapest, and quickest interventions in almost all sectors as well as having the least risk of negative side-effects. This is true even though the net energy savings will be less than a simple analysis would predict because efficiency improvements can stimulate demand by making the associated energy service less expensive. Even so, to expend great amounts of resources to develop new sources of energy makes no sense if they are used poorly. Additionally, many technologies for improved efficiency are already available, but various policy, information, and economic barriers prevent their implementation.

Correspondence to:
Prof Andy Haines, Director’s Office, London School of Hygiene and Tropical Medicine, Keppel Street, London WC1E 7HT, UK
andy.haines@lshtm.ac.uk

Panel: Technology and policy options for mitigation of greenhouse-gas emissions from electricity generation and use of energy in different sectors

1 Energy efficiency in homes, industry, transport, and commerce
   - Vehicle fuel economy. Pacala and Socolow[18,19] draw attention to savings that would arise if average vehicle fuel efficiency were raised from 30 to 60 mpg. The hybrid vehicle, to name just one possibility, could take us a long way down this route, as could the hydrogen fuel-cell vehicle. Congestion pricing, which is becoming increasingly practicable thanks to developments in information technologies, is another practice that would improve fuel efficiency in transport
   - Buildings. There is a large industry engaged in improving efficiency of space heating, cooling, water heating, lighting, and appliances such as air conditioning and refrigeration
   - Industry and commerce. There is a similarly large industry engaged in improving efficiency in use of heat, light, motive power, air conditioning, and refrigeration in industrial processes and commerce
   - Use of combined heat and power "cogeneration" to generate electricity and heat simultaneously for industry and buildings with overall efficiency of fuel use of over 75% compared with 50% for standard electricity generation
   - Smart grids with distributed, regional and central power generation, and technologies to reduce demand and optimise distribution (eg, to critical areas during peak periods), can constitute a clean, efficient, robust, and resilient energy system

2 Substitution of natural gas for coal in power generation, which reduces both greenhouse-gas emissions and air pollution

3 Use of coal and natural gas for electricity generation, with carbon dioxide being captured and stored in geological formations and oceans (carbon capture and storage). This is still a fairly unresearched approach which has been topic of an IPCC special report[20] (webpanel 1)

See Online for webpanel 1

4 Nuclear power for electricity generation. This is controversial because of risks of proliferation, terrorist attack, and waste storage, as well as large up-front capital costs. However, a range of nuclear fission technologies to improve safety and reduce cost is now available. Detailed discussion of the strengths and weaknesses of various designs have been reviewed elsewhere.[21] Webpanel 2 summarises the pros and cons of nuclear power[22,23]

See Online for webpanel 2

5 Production of hydrogen from gas and coal, with carbon dioxide being captured and stored. This could be a low-cost route to opening up hydrogen economy. The hydrogen option is, of course, not a primary energy resource, but a means of storing and using renewable and nuclear energy, and also energy from fossil fuels while avoiding carbon emissions to the atmosphere if carbon dioxide is captured and stored. Hydrogen could serve major energy markets—eg, for transport fuels, either for fuel cell or internal combustion engine vehicles; for heating and power in homes, industry, and commerce; and for the industrial fuel market

6 Renewable energy. This is a diverse resource, and far more plentiful than often thought
   - Onshore and offshore wind. Offshore resource is especially abundant in Europe, while extensive wind farms are being developed on US plains
   - Wave and tidal energy, including tidal streams
   - Solar photovoltaics are especially promising in developing regions, where incident solar energy is two to three times greater than in the UK and energy is more uniformly distributed throughout year
   - Solar thermal technologies, both for heating and for power generation. Again, these are most promising in developing regions but large arrays are being erected as far north as Canada
   - Combustion of landfill gas, a natural byproduct of decomposition of solid waste in landfills, comprised mainly of carbon dioxide and methane. Combustion prevents release of methane
   - Biomass combustion for heat and power, liquid fuels for transport, and methane for electricity generation. In developing regions, energy from biomass can be produced in ways that could restore degraded lands, forests, watersheds, and ground water resources.[24] Use of bioplastics derived from corn, cellulose, soya, etc, and biopaints and wood products from sustainable forestry (preserving carbon sinks and biodiversity) can also help to reduce greenhouse gases
   - Organic biomass wastes for combined heat and power, a practice widely used in Europe, and also for producing biofuels for transport
   - Geothermal energy, which could become a substantial resource given progress in the oil and gas industry with deep drilling technologies. In some countries (eg, Iceland) it is the predominant energy source for centralised power generation; geothermal heat-pumps using sub-surface temperature differentials can be used for individual buildings or building complexes

7 Production of hydrogen by electrolysis from renewable energy and nuclear power, again for use as fuel for homes, commerce, industry, and transport

8 Production of hydrogen from biomass, with carbon capture and storage. This roughly doubles the carbon value of this resource, first for producing fuel with low carbon emissions, second for scrubbing and sequestering carbon dioxide from atmosphere

How greenhouse-gas emissions can be stabilised

One approach to illustrating potential solutions to the major challenge of stabilising emissions of greenhouse gases is the concept of stabilisation wedges, where a wedge is 1 gigatonne of carbon per year of emission savings in 2054 achieved by a single strategy.[18,19] The approach focuses on carbon dioxide because it is the predominant greenhouse gas, although similar strategies could be devised for other greenhouse gases. Implementing seven wedges of this magnitude, it is argued, should put the world on track for stabilisation of greenhouse-gas concentrations at less than double pre-industrial levels. Figure 1 presents an illustrative plan of the first 50 years of action required to achieve this goal. The proposal assumes that emission rates must fall in the second half of the century, declining to net zero emissions near the end of the century. Although there are major uncertainties, this approach does indicate the likely magnitude of change required and the mix of policy options. Table 1 summarises some of the strategies available. Most of these strategies have the potential to improve health in the near term by reducing exposure to air pollution, and some have the potential to bring added benefits through increased physical activity. A few bring with them potential but poorly quantified threats to public health—eg, the safety issues associated with a hydrogen economy, the environmental health risks associated with nuclear waste, and the potential for nuclear proliferation or terrorist attacks on an expanded nuclear power programme. The table omits two strategies that we consider could make important contributions to reducing greenhouse-gas emissions and that are outlined in this article—limiting livestock production and human population policies.

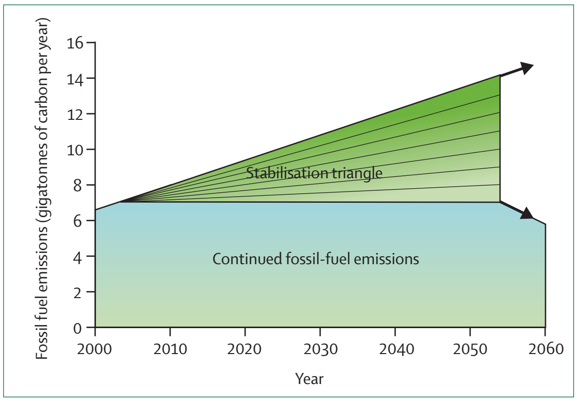

Figure 1: The stabilisation triangle[18,19]
Stabilisation triangle is idealisation of first 50 years of action required to achieve stabilisation of atmospheric carbon dioxide concentration below double the pre-industrial concentration. Triangle is bounded by: (1) year 2054; (2) flat trajectory of constant global carbon emissions at current rate of 7 gigatonnes of carbon a year, intended to approximate first 50 years of 500 ppm stabilisation trajectory; and (3) ramp trajectory in which emissions climb linearly to twice current rates, intended to approximate business-as-usual—ie, world inattentive to global carbon. Stabilisation triangle is divided into seven wedges of avoided emissions, each of which grows linearly from zero today to 1 gigatonne of carbon a year in 2054. Adapted with permission from reference 18.

Sectoral analysis and health effects

Assessment of the effect of energy, transport, and agricultural policies on health will provide better evidence to guide policymakers' choices about the appropriate mix of strategies to abate greenhouse gases. Full awareness of the health risks should lead to both actions taken to achieve near-term benefits to health and a reinforced policy recognition of the need for long-term mitigation of climate change. Assessment of health effects should include both the direct effects of different technologies and policies on health and, where feasible, the indirect effects—eg, of extraction and transport on the environment, or effects on agricultural production and economic growth. A lifecycle analysis of the potential risks for health and the environment can help differentiate safe, no-regrets solutions from those that warrant further study.

Health effects of climate change mitigation policies in the energy sector

There have been attempts—eg, by the Working Group on Public Health and Fossil Fuel Combustion[25]—to estimate the global health benefit of reduced exposure to outdoor air pollution from particulates under a mitigation scenario such as that envisaged under the Kyoto Protocol. Such an approach involved several simplifying assumptions and the resulting estimates of avoided deaths should be seen as indicative of the approximate contribution of mitigation policies to improving health. Several other studies have estimated the secondary benefits of reducing air pollution as a result of reductions in fossil-fuel emissions.[26]

The degree of health benefit will depend markedly on the trajectory of emissions reduction which is followed, relevant differences between the current source of energy and the alternative, and the baseline level of air pollution. For example, switching from combustion of natural gas to wind or solar power would have little effect on air pollution despite reducing greenhouse-gas emissions whereas a switch from coal would have a major effect. Direct health benefits as a result of reduced air pollution will be particularly large where that pollution occurs in close proximity to human beings, thereby causing high exposure—eg, in households.

Renewable energy technologies, such as solar thermal, geothermal, solar photovoltaic, and wind, seem to have few or no adverse consequences for health and great potential for benefit. However, a small proportion (less than 5%) of people living near wind turbines are annoyed by the noise. Annoyance correlates with decibel level, is more common in rural than in urban areas, and is more likely where terrain is hilly or rocky.[27] Smart grids will enable use of centralised generation along with regional and smaller dispersed energy generation with renewables and combined heat and power, and permit greater interactivity of end users with the grid. They are the subject of much research, including a major programme funded by the European Union (EU).[28] Where grids are inadequate, electricity from renewable sources can pump water, power clinics, light homes, cook food, and drive development. Clean distributed generation and smart grids should improve coping and resilience in the face of weather extremes (adaptation), reduce emission of greenhouse gases (mitigation), and create jobs in the new technologies.

The construction of large dams for hydroelectricity, however, can result in displacement of populations and other adverse effects. There is considerable dispute about official figures for people who are displaced, with allegations that they are often under-represented by governmental authorities.[29] Since many displaced people may be landless peasants, they are inadequately compensated for loss of livelihoods where compensation depends on land holdings. A range of public-health problems related to dams have been documented, including increases in the prevalence of schistosomiasis and the introduction of Rift Valley fever. Even small dams

	Effort by 2054 for one wedge, relative to 14 gigatonnes of carbon per year*	Comments, issues
Energy efficiency and conservation		
Economy-wide carbon-intensity reduction (emissions/$GDP)	Increase reduction by additional 0·15% per year (eg, increase US goal of 1·96% reduction per year to 2·11% per year)	Can be tuned by greenhouse-gas policies
Efficient vehicles	Increase fuel economy for 2 billion cars from 30 to 60 mpg	Car size, power
Reduced use of vehicles	Decrease car travel for 2 billion 30-mpg cars from 10 000 to 5000 miles per year	Urban design, mass transit, promotion of active transport (walking, cycling), telecommuting
Efficient buildings	Cut carbon emissions by a quarter in buildings and appliances projected for 2054	Weak incentives
Efficient baseload coal plants	Produce twice today's coal power output at 60% instead of 40% efficiency (compared with 32% today)	Advanced high-temperature materials
Fuel shift		
Gas baseload power for coal baseload power	Replace 1400 GW 50%-efficient coal plants with gas plants (four times current production of gas-based power)	Competing demands for natural gas and limited supplies
CO_2 capture and storage (CCS)		
Capture CO_2 at baseload power plant	Introduce CCS at 800 GW coal or 1600 GW natural gas (compared with 1060 GW coal in 1999)	Technology already in use for H_2 production
Capture CO_2 at H_2 plant	Introduce CCS at plants producing 250 megatonnes of H_2 per year from coal or 500 megatonnes of H_2 per year from natural gas (compared with 40 megatonnes H_2 a year today from all sources)	H_2 safety, infrastructure
Capture CO_2 at coal-to-synfuels plant	Introduce CCS at synfuels† plants producing 30 million barrels a day from coal (200 times Sasol‡), if half of feedstock carbon is available for capture	Increased CO_2 emissions, if synfuels are produced without CCS
Geological storage	Create 3500 Sleipners§	Durable storage needed to prevent long-term leakage of carbon dioxide
Nuclear fission		
Nuclear power for coal power	Add 700 GW (twice the current capacity)	Nuclear proliferation, terrorism, waste
Renewable electricity and fuels		
Wind power for coal power	Add 2 million 1-MW-peak windmills (50 times current capacity) "occupying" 30×10^6 ha, on land or offshore	Multiple uses of land because windmills are widely spaced
Photovoltaic (PV) power for coal power	Add 2000 GW-peak PV (700 times current capacity) on 2×10^6 ha	PV production cost
Wind H_2 in fuel-cell car for gasoline in hybrid car	Add 4 million 1-MW-peak windmills (100 times the current capacity)	H_2 safety, infrastructure
Biomass fuel for fossil fuel	Add 100 times current Brazil or US ethanol production, with use of 250×10^6 ha (a sixth of world cropland)	Biodiversity, competing land use
Forests and agricultural soils		
Reduced deforestation, plus reforestation, afforestation, and new plantations	Decrease tropical deforestation to zero instead of 0·5 gigatonnes of carbon per year, and establish 300 million ha of new tree plantations (twice current rate)	Land demands of agriculture, benefits to biodiversity from reduced deforestation
Conservation tillage¶	Apply to all cropland (ten times current usage)	Reversibility, verification

*Under a business-as-usual scenario without attention to greenhouse-gas emissions. The list of strategies is not exhaustive. †Synthetic liquid fuels obtained from coal, natural gas, and other fossil fuels and can also be produced from biomass. ‡South African company that is largest producer of synfuels such as diesel and petrol from coal and natural gas. §Carbon dioxide extracted from gas production, from Statoil's Sleipner West Field in the North Sea, has been pumped under sea bed for storage since 1996, which avoids paying a carbon tax equivalent of $50 per tonne of CO_2 released, imposed by Norwegian Government. ¶Minimum cultivation to leave soil intact and crop residue in place, which could promote carbon sequestration and protect against soil erosion. Adapted from reference 18 with permission.

Table 1: **Strategies available to reduce carbon emission rate in 2054 by 1 gigatonne of carbon per year, or to reduce carbon emissions from 2004 to 2054 by 25 gigatonnes of carbon**[18,19]

can have an adverse effect, such as the increase in malaria that has been documented in Ethiopia.[30] However, preventive measures, including engineering control mechanisms, can be taken to reduce the adverse effects of dams on health.

Nuclear power is undoubtedly the most contentious energy source in high-income countries because of public concerns about accidents, proliferation, terrorist attacks, and waste storage. The second article in this Series[31] suggested that nuclear power compares favourably with fossil fuels in terms of expected effects on health, but the analysis did not take into account the difficult-to-quantify issues that evoke public concerns.

Developments in reactor design can reduce the risk of accidents by incorporating a range of safety features and all modern reactors include separate capability for emergency shutdown in the event that primary control via the control rods is lost.[21] The Non-Proliferation Treaty obliges all signatory countries to accept International Atomic Energy Agency safeguards on fissionable material in all peaceful nuclear activities, including a rigorous inspection regime.[32] The Royal Society has made the case that better policies are needed for the storage of nuclear waste in the UK, much of which is a legacy of civilian and military programmes in the 1950s, irrespective of whether new nuclear plants are built.[33] The Intergovernmental Panel on Climate Change (IPCC) has concluded that, despite public concerns, in view of the costs in relation to other options, nuclear power could increase from providing 16% of the world's electricity currently to 18% in the future, as part of the response to climate change mitigation.[15] If the current ageing capacity for nuclear power generation is not at least replaced in a country like the UK, the prospects of radically cutting greenhouse-gas emissions will be even more daunting. Currently the UK relies on nuclear power for about 20% of its electricity and all current nuclear power stations are scheduled to close within 30 years. For this reason the Royal Society has stated "in the short to medium term, it is difficult to see how the UK can reduce dependence on fossil fuels without the help of nuclear power".[34] In view of the magnitude of the challenges, consideration must be given to using all the approaches available to reduce greenhouse-gas emissions, but policymakers must be prepared to foster public debate and modify their choices as time reveals their true worth.

Agriculture and food production

Climate change has serious implications for food production, processing, and distribution. Although some models of the effect of climate change on food production suggest that global grain production might not change much, at least in the medium term, with decreases in low latitudes being offset by increases at high latitudes, the distributional effects have major consequences for poor people. According to some scenarios, 20–40 poor and food-insecure countries with a total population of 1–3 billion people could lose on average 10–20% of their cereal production by the 2080s.[35] Additionally, changes in the ranges of agricultural pests and diseases with warming winters, and infestations associated with extremes (eg, droughts favour locust, whiteflies, and aphids), could precipitate extensive losses of crop yields.[36]

Under most climate change scenarios, Sudan, Nigeria, Senegal, Mali, Burkina Faso, Somalia, Ethiopia, Zimbabwe, Chad, Sierra Leone, Angola, Mozambique, and Niger—currently with about 87 million people who are undernourished—are projected to experience a fall in cereal production potential. Over the past 30 years, rain across the Sahel has already declined by 25%, contributing to hunger from Niger to Darfur and across to Somalia.[37] However, most, if not all, of these countries currently operate well below their existing production potential because of a range of factors, mainly political and economic, and could potentially increase their food production with improved policies and practices.

The 2007 IPCC report[38] and a recent report from a UN Framework Convention on Climate Change workshop[37] project continued drying of sub-Saharan Africa with mounting effects on health, crop yields, livelihoods, refugees, and conflict. Intense extremes and wide sequential swings in weather could mean that cumulative consequences lie in store for nations ill-prepared to adapt to climate change.

The prospect that food crops could be diverted to provide biofuels for transportation raises the need to prioritise food security in vulnerable areas and underlines the need for policies that do not reduce food crop production. Options that exploit the possible agricultural and forestry investment opportunities arising from increased biofuel markets in high-income countries, and couple them to the development of sustainable land-use policies in low-income countries, need urgent encouragement.

Fossil energy used directly in agriculture is only about 3–4% of the total consumption in industrial countries, and an even smaller fraction in developing countries. However, food production, especially livestock, is a major source of greenhouse-gas emissions, including methane from ruminant digestion, nitrous oxide from fertiliser use, and carbon dioxide from felled vegetation and exposed soil. Indeed when these factors are taken into account, the global emissions from agriculture seem to be greater than those from transport overall.[9,39] Livestock production is expanding rapidly, especially in low-income and middle-income countries. Land clearing to produce livestock feed—eg, soy and corn—compounds the contribution to climate change.

Because the scope for reducing greenhouse-gas emissions per unit of animal product is currently limited, reducing the demand for animal products—especially for red meat and dairy products—has greater potential for reducing the climate consequences of agriculture. Reducing the consumption of such animal products in high-income countries is unlikely to lead to any adverse effects on health and would probably result in modest health benefits—eg, from reductions in the incidence of cardiovascular disease and bowel cancer.[40] If livestock's contribution to greenhouse-gas emissions could be capped to help mitigate climate change, reductions in consumption of animal products, particularly from ruminants in rich countries, would allow increases in poor countries, bringing health benefits to both. For example, if meat consumption was to converge at an average of around 90 g meat per person a day, this would entail a more than 70% reduction for people in the USA and around a three-fold increase for people in Nigeria.

Meanwhile, there is a need to expand the supply of agricultural outputs in general, to eliminate malnutrition and to feed a growing world population. To achieve this goal will require modern inputs, otherwise low productivity, hunger, and continued poverty will result—the last, in part, because of the continuing reliance on human power.

Bioenergy

The traditional use of biomass as fuel is often inefficient, with a conversion efficiency of only 2–20%, and results in local air pollution as well as adverse environmental effects. However, modern bioenergy technologies offer considerable promise, with conversion efficiencies of up to 90%.[41] Bioenergy has an expanding role as the source of the energy services required for achieving higher agricultural productivity, alleviating poverty, and addressing social, economic, environmental, and health issues if the right policies are put in place, especially in the household fuel sector, for which there are many opportunities for addressing these goals at low costs.

Improved stoves with chimneys can reduce indoor particulate pollution and thus have the potential to reduce the 1·6 million annual premature deaths caused by indoor air pollution. Worthwhile reductions in personal exposure of 30–50% could be attained.[42] The Chinese National Improved Stove Program introduced some 180 million improved chimney stoves during the 1990s, but unfortunately has not moved to promote more advanced generations of stoves needed to lower exposures to acceptable levels.[43] Cleaner fuels such as kerosene and liquefied petroleum gas produce much lower levels of air pollution and are therefore likely to result in substantially greater health gains; but they are often more expensive. More advanced biomass stoves that use pellets, blowers, or other means to achieve cleaner combustion offer substantial promise to lower exposures even more. Recent analyses indicate that, in many areas, biomass stoves that have improved efficiency seem to have the most favourable cost-effectiveness ratio, followed by kerosene.[44] However, the implementation of culturally acceptable improved-efficiency stoves has been slow, especially in Africa. More work is required to develop and disseminate acceptable, low-cost, and efficient stoves and to ensure that installers and users are trained properly. However, in some areas scarcity of wood could in future make other energy sources more attractive.

Although wider access to electricity is needed, in most areas it is still too expensive to be used widely for major cooking tasks. In South Africa, for example, one study showed that only 27% of electrified homes in the study village used electricity for cooking because of the expense.[45] Specialised cooking devices such as rice cookers and insulated hot-water kettles, however, are cost-effective in many areas of the world. Electricity generated from biomass could help address the energy needs of such communities, including through the use of biomass gasification which produces much lower greenhouse-gas emissions and lower emissions of some, but not all, other pollutants, compared with coal. In addition to their major potential effect on public health, with appropriate policies, modern uses of biomass have great potential to benefit the economies of countries at both the micro and macro scale through local jobs and reducing the need for oil imports for oil-poor developing countries.

Biofuels can also be used for transport but, because of the diversity of supply, conversion, and use options, the greenhouse-gas emissions can vary from those which are worse than the fossil fuel reference case to pathways that could remove greenhouse-gas emissions. However, with the proviso that there is no clearance of forests or destruction of peat lands, most studies suggest that, compared with petroleum fuels, there is a reduction of greenhouse-gas emissions.[46] At present, biofuels are a fairly expensive way of reducing greenhouse-gas emissions in many countries but, in Brazil, ethanol from sugarcane is competitive when oil costs more than US$50 a barrel. The dependence of these types of biofuel crops on nitrogen fertiliser, with its associated fossil-energy inputs and nitrous oxide emissions in production and use, needs further investigation and offers the potential to reduce greenhouse-gas emissions further.

In Indonesia and Malaysia, vast stands of tropical rainforest growing on peat swamps are being burnt and cleared to make way for palm trees to produce oil for human consumption and biodiesel use, creating a huge pulse of carbon emissions and biodiversity loss. As a result, there are serious concerns about the potential adverse effects of biofuels that will need to be addressed by policies that promote their use.[47] To produce 20% of the demand in 2020 for oil for transport use would require up to 250 million hectares of land. However, there is scope for using the 2 billion hectares of land worldwide that are currently degraded or abandoned, nearly 500 million of which are in Africa alone.[24,48]

Biodiesel tends to produce fewer fine particles than standard diesel, with potential health benefits. Although most emissions from ethanol fuel are similar to standard petrol, a recent US study suggests that for Los Angeles, CA, burning 85% ethanol/15% gasoline (v/v) fuel would increase ground-level ozone or smog compared with burning petrol.[49] Formaldehyde and acetaldehyde also tend to be produced in higher concentrations from the combustion of ethanol. Overall, the direct health effects may be similar to—or slightly worse than—petrol, but will depend on the baseline emission standards; changing technologies could affect the outcome.

In Brazil the air quality in urban centres has improved since ethanol has been used as an automotive fuel but the burning of sugar cane before manual harvesting for ethanol production causes widespread particulate air pollution in the plantation areas, and is associated with increases in hospital admissions for asthma,[50] underlining the importance of undertaking an assessment of the health effects of the full lifecycle of any energy source.

Agriculture and bioenergy need to modernise as a precondition for development, agricultural growth, poverty alleviation, and environmental sustainability.[51,52] But achieving all of these goals simultaneously is likely to be one of the major policy challenges of the 21st century. To develop and implement, internationally agreed standards and effective approaches to certification will be essential, as will alignment of international rules of trade (eg, subsidies and tariffs) to protect society from the potential adverse effects of inappropriate biofuel policies.[46]

Transport

The transition to a low-carbon low-energy transportation system involving substantially increased levels of active transport has the potential to bring considerable health co-benefits, as outlined elsewhere in the Series.[53] Road traffic crashes account for around 1·2 million deaths each year,[54] with ten times as many people seriously injured. Urban air pollution, much of which is transport related, causes around 800 000 premature deaths a year.[3,55] Reductions in the volume and speed of traffic, especially in cities, will mitigate climate effects, reduce injury rates, and improve air quality.[54] Because road danger is a strong disincentive to walking and cycling, safer streets could lead to a virtuous circle of increasing levels of active transport. This increase will have important consequences for physical activity and personal energy balance, and would affect rates of obesity, diabetes, and cardiovascular disease.[56] Other co-benefits would include improved equity in access, reduced noise and congestion, greater energy security, and benefits arising from the alternative uses of the considerable resource costs of road transport.

Clearly, the decarbonisation of transport is not only essential to averting climate change, but has huge potential to improve public health. Greenhouse-gas emissions from the transport sector can be reduced through a combination of trip substitution (eg, by telecommunications), improved technology and vehicle efficiency, trip distance reduction, and a shift in modes of transport. On their own, technological developments will not be sufficient because of predicted increases in motor vehicle sales and use. From a public-health perspective, modal shift offers the greatest opportunity for benefit. A shift to cycling, walking, and public transport also lowers energy use, which makes it easier to satisfy demands from non-fossil fuel sources such as biofuels.

How achievable is this? Much of the answer lies in the reconceptualisation and redesign of cities. Half of the world's population now lives in cities. Urban areas account for 78% of anthropogenic carbon emissions.[9] The spatial design of cities is a key determinant of transport sustainability. High-density land use means shorter distances that can be covered readily by walking and cycling, and high-occupancy public transport. Such measures need to be accompanied by policies that support walking and cycling, including legal priority, reallocation of street space and time, making trips more pleasant and attractive, and financial incentives. Cycling accounts for about a third of trips in some European cities[57] but for less than 1% of trips in others. Cycling also has considerable potential in low-income and middle-income cities where currently most journeys are by foot or public transport. Financial incentives can include converting fixed costs of motor vehicle use into distance-based charges that would send a more appropriate price signal and would discourage car use for short journeys. The expansion of car clubs as an alternative to car ownership, especially in urban areas, could contribute to reductions in unnecessary car use.

Although road building accounts for most transport-related international aid, the extent to which road construction benefits poor people remains open to question. Most of the world's population will never own a car and local transport surveys show that road building fails to meet the transportation needs of poor people, for whom most trips are off-road by foot and over short distances, carrying small loads for subsistence needs.[58] Wheeled non-motorised modes such as bicycles and carts are substantially more energy efficient than walking and headloading (ie, carrying items on one's head). Increasing access to these methods of transport, combined with a substantial increase in the provision of foot and cycle infrastructure, would be a sustainable way to improve health and development. Such transport can potentially reduce the large time burden of carrying water and firewood and hence free time for education, non-subsistence production, and other activities.

Beyond its effects on climate and aircraft noise, reducing air transportation is unlikely to bring important health co-benefits, with the possible exception of the role of aviation in the global spread of infectious diseases. Substantial gains in the energy efficiency of aviation are unlikely and, in any event, the growth in volume is predicted to far outweigh efficiency gains in the medium term. Aviation biofuels are under development but they would compete with other demands on bioenergy. Current worldwide plans for expansion of aviation could well be unsustainable from a greenhouse-gas standpoint; efficient, equitable, and effective methods of limiting the use of air travel will be needed. Such methods would probably work best through economic incentives such as taxes, and by focusing initially on short-haul flights for which rail travel offers a viable alternative.

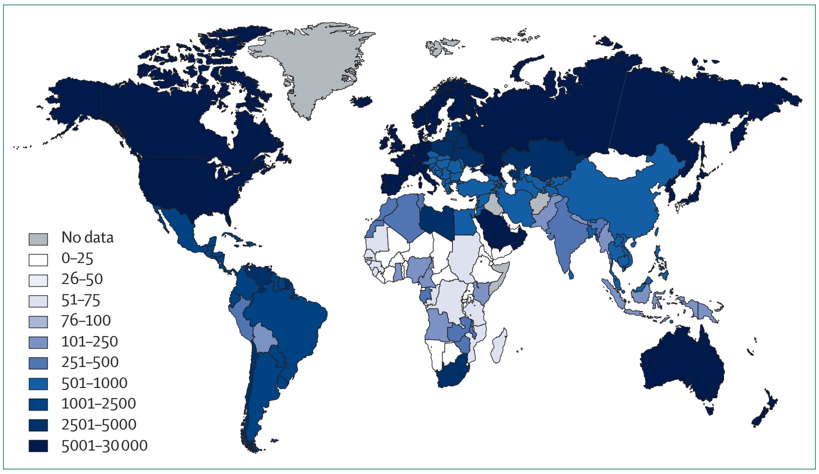

Figure 2: **Electricity use in kWh per head, by country, 2001**
Adapted from reference 2.

Housing and the built environment

The co-benefits of a transition towards cleaner and more efficient use of energy in the urban environment were outlined in this Series.[59] The twin objectives of reducing greenhouse-gas emissions and adapting to climate change will entail measures that usually also help improve the quality of the built environment for local residents—eg, by increasing the numbers of trees that provide shade against the sun, by reducing the density of road vehicles and their emissions, by making spaces more attractive and safer for walking, cycling, and outdoor recreation, by ensuring greater energy efficiency in homes that are easier to keep both appropriately ventilated and warm in winter at lower cost,[60] and by switching energy supplies for commercial and residential buildings to more renewable, less polluting sources.

Much of the air pollution in urban settings (at least in terms of secondary particles) arises from distant rather than local sources through the transport of polluted air masses.[61] Urban air pollution can therefore be considered in part a regional problem, and the improvement in local air quality will be aided considerably if neighbouring regions make similar energy adjustments.

Technology alone could be insufficient to bring about substantial reductions in energy use, however, because of the propensity for people to use the resources they can afford—eg, responding to increased home heating efficiency by increasing indoor temperature with no net change in energy use, (which could sometimes be appropriate from a health perspective because cold homes are associated with increased winter mortality in the UK[62]). Furthermore, the turnover in housing stock is often extremely slow. In the UK, as in many other settings, most of the houses that will be lived in over this century are already built. Even if it is now possible to construct dwellings with very low energy needs, it will be many years before such dwellings begin to make a substantial impression on housing-related carbon dioxide emissions, particularly if the (appreciable) energy consumption involved in construction is taken into account. Energy efficiency retrofitting can in theory be applied to a large part of the existing stock, but the effect on greenhouse-gas emissions might be disappointing, except where a switch is made to renewable energy sources. Another factor is the inherent inertia of strategic planning imposed, for example, by the fact that urban environments are long established in their basic layout and not easily alterable. Thus, in the short term, there is limited capacity to reverse unwelcome major developments of the past. Nonetheless, there is now growing understanding of the measures that can improve built environments in ways that both reduce energy use and promote health. So-called green buildings combine the use of renewable energy and energy efficiency measures and the use of non-petrochemical products and wood from sustainable forestry. A substantial effect will be achieved not through one major intervention, but through several parallel steps, which include behavioural change, planning, targeted programmes, and enabling policies.

Millennium Development Goals, energy services, and climate change

The UN Millennium Development Goals (MDGs) influence the development policies of many nations. However, power generation and energy use do not feature prominently in the MDGs although, as outlined in the first article of this Series,[63] equitable access to clean energy is essential for their attainment. They are framed in a way that gives little explicit recognition to the fundamental role of environmental sustainability as a prerequisite for the attainment of most other goals, although Goal 7 refers in general terms to the need to integrate the principles of sustainable development into country policies. The only specific energy-related indicators are 27, 28, and 29 linked to Goal 7. Indicators 27 and 28 refer to the gross domestic product (GDP) per unit of energy use and carbon dioxide emissions per head, respectively, and indicator 29 refers to the proportion of the population using solid fuels.[64] A review of the ways in which energy issues are addressed in national MDG reports showed much variation and frequently omission, with 42% of 112 country reports having little or no mention of energy and only 26% having considerable coverage.[65]

Around 2·4 billion people do not have access to clean fuels for cooking and heating and 1·6 billion people do not have access to electricity.[66] Figure 2 and figure 3 show electricity use per head by country and deaths per million from indoor smoke from solid fuels.[2,3] There is a real and synergistic opportunity to link attainment of the MDGs with climate change mitigation and simultaneous health improvement, but this is unlikely to happen without serious coordinated effort at the global level.

Future energy uses by the energy poor

Cooking and heating will probably remain the most energetically dominant areas for some time among poor people, and a key part of the MDG Energy Vision, developed by the Stockholm Environment Institute to show the importance of development of improved access to clean energy, involves the switch by many people at present mainly dependent on biomass to modern fuels (webpanel 3).[66] This switch should lead to immediate health improvements, especially for women and young children, who tend to spend most time near smoke. We have adapted the targets in the Vision statement, particularly to address the use of contaminated coal in China[67] and the need for improved access to electricity by rural populations. Biogas, produced by anaerobic digestion of organic waste, is an example of a renewable fuel that can burn as cleanly as liquid petroleum gas, producing very little particulate pollution, but with substantially lower emissions of greenhouse gases than many alternatives.

Mechanical energy—ie, the energy that is possessed by an object due to its motion or its stored energy of position—is especially important in the poorest areas, where it is the means through which household, agricultural, and transport work can be transformed. A study in Mali showed that the provision of a multifunctional platform, powered by a small diesel motor for tasks such as pumping water, grinding grain, and pressing nut and vegetable oil, has allowed women to reduce their chores by around 2·5 h a day on average and to increase their income from agricultural activities by $0·32 a day which, considering that about 10% of Mali's population earns under a dollar a day, is substantial.[68] Additionally, the proportion of girls attending school almost doubled as a result of the reduction of female household labour requirements. In a project looking at cost estimates of energy provision to meet the MDGs in Kenya, mechanical energy was found to be cheap ($1 per head) and to have the most substantial effect on development.[69]

Energy services provided by electricity allow increased productive time through lighting, health care through refrigeration, education through computers, and economic development through mechanical energy. They can also reduce gender inequality because girls and women are often primarily responsible for collection of fuel and water and domestic tasks. Access to electricity can also help to alleviate poverty. A study in the Philippines suggested that a family could benefit by $80–150 per month from electrification, a substantial sum for poor families.[70]

How much energy will this need in comparison to the world's total energy use?

Different studies have quantified the energy needed to meet development goals. The Stockholm Environment Institute estimated the total level of energy consumption to meet the MDG Energy Vision is about 900 terawatt hours equivalent of energy, most of it in the form of energy for cooking.[66] This is less than 1% of the current global annual energy consumption. Another estimate suggested that to provide those whose primary cooking fuel is biomass and all those with no access to electricity with energy for cooking and electricity for light would need just over 1% of the world total primary energy demand in 2004.[69] If all traditional use of biomass was replaced with liquid petroleum gas by 2015, oil demand would rise by 0·069% of the projected world demand in the reference scenario, or 0·072% of the alternative policy scenario according to the World Energy Outlook.[12]

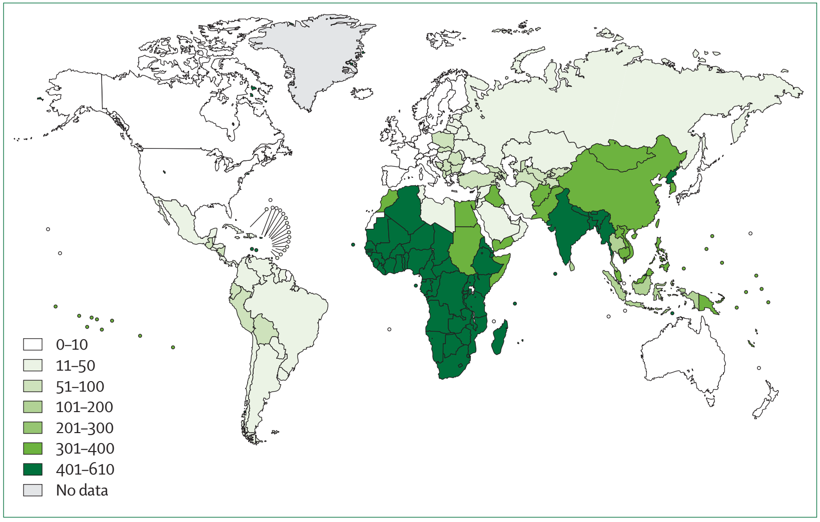

***Figure 3*: Estimated deaths per million for 2000 from indoor smoke from solid fuels**
Adapted from http://www.who.int/heli/risks/indoorair/en/iamap.pdf.

See Online for webpanel 3

Despite the relative expense, there are a growing number of countries in which a substantial contribution to energy requirements is being met from clean renewable sources. These include the use of photovoltaic systems to provide energy to 50 000 homes of nomads in Mongolia and more than 4500 wind generators providing up to 200 watts. In Nepal about 1% of households have access to solar energy and nearly 2% to energy from micro hydro-schemes.[71] In a recent gusty period, wind power provided 27% of Spain's electricity and, over a year, the contribution was 9%.[72]

Because poor people, especially in rural areas, could be excluded from participation in the use of such technologies because of the high costs and lack of credit, clean development funds for adaption and mitigation can help facilitate the clean energy transition that must take place on a global scale if development goals are to be met while stabilising the climate.

Of course the energy requirements for achieving the MDGs should be seen as a bare minimum component of the larger secure supply of energy that is required for socioeconomic development in general. The indications are that developing countries aspire to a similar standard of living as that enjoyed by countries within the

Organisation for Economic Co-operation and Development (OECD), and more than 70% of the increased demand for energy over the next 30 years is projected to come from the non-OECD countries.[73]

How climate change mitigation policies could help reduce the vulnerability of poor populations to climate change

Poor populations are likely to suffer disproportionately from the adverse effects of climate change.[4,5] Their vulnerability could be reduced in several ways by improving access to clean energy—eg, reliable energy supplies are required for lighting, maintaining the cold chain for vaccines and other essential equipment in health facilities, and to power telecommunications equipment.

Clean energy and adequate water quantity and quality are essential to good public health, agriculture, and development. In view of the growing water crisis (from overuse, depletion of soils, and irregular precipitation accompanying climate change) in many countries, the need to pump, decontaminate, and desalinate water could become a major objective for the clean energy transition.

By contributing to poverty reduction, improved access to such energy sources can lead to increased resilience in the face of climate change. Modernisation of agriculture in low-income countries, which reverses land degradation and increases food yields, could help to buffer vulnerable populations from reductions in food availability induced by climate change while improving the capacity of soil to act as a carbon sink.

Economic policies to promote climate change mitigation

The Stern review[9] described a range of economic policies for the mitigation of and adaption to climate change. It estimated that to deploy low-carbon technologies on the scale required to stabilise carbon dioxide equivalent (CO_2e) concentrations at under 550 parts per million (ppm) would entail an incremental cost in the range –1% to 3·5% of GWP a year. This wide range reflects the uncertainties about the future costs of the alternatives to fossil fuels and, equally, the future prices of fossil fuels themselves. High future prices for oil and gas, whether the product of international disputes or, in the case of oil, by "easy oil" (ie, oil that is easily found and extracted) running short, will make the alternatives increasingly attractive. The range is of course large in absolute terms (1% of GWP is projected to exceed $1 trillion per year by 2050), but small in relation to its expected growth over the next 40–50 years. GWP is currently $35 trillion a year but is expanding at 2–4% per year, and is expected to exceed $100 trillion a

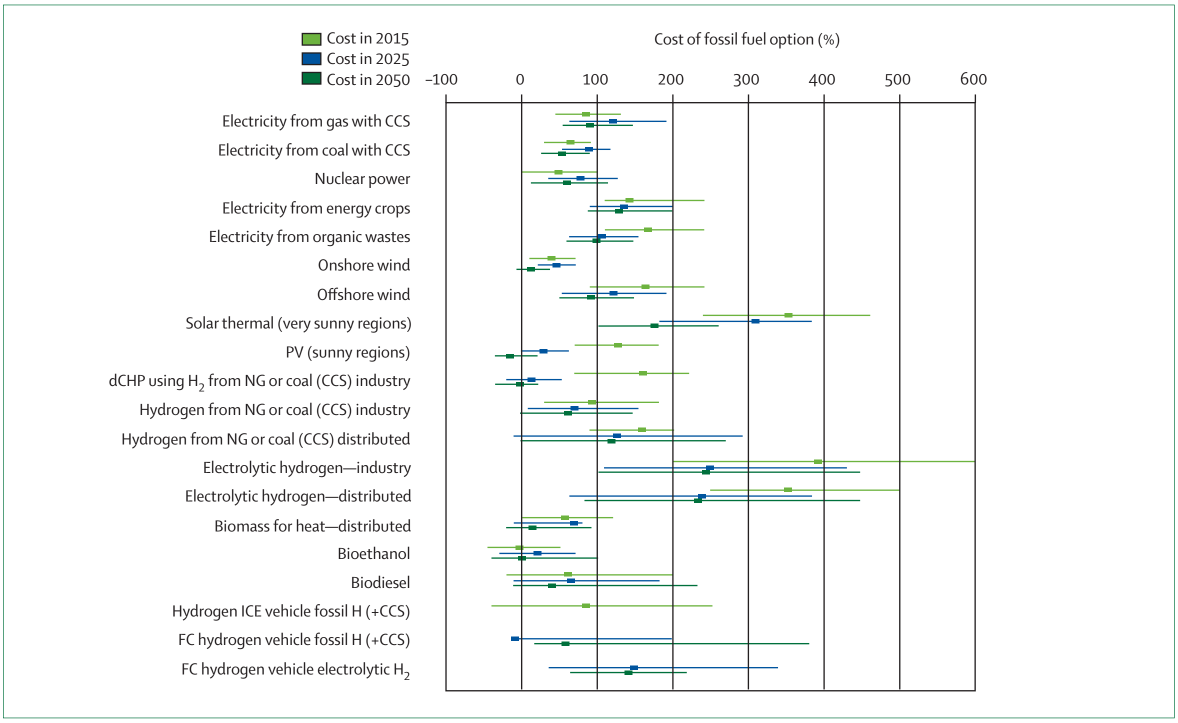

***Figure 4:* Costs of energy technologies to constrain emissions to today's levels in 2050, expressed as amount in percent by which they exceed costs of fossil-fuel alternative in 2015, 2025, and 2050[9]**

CCS=carbon capture and storage. dCHP=domestic combined heat and power. FC=fuel cell. ICE=internal combustion engine. NG=natural gas. PV=photovoltaics. 0% indicates that cost is the same as fossil-fuel option. Negative values indicate that the technology is cheaper and positive values that it is more expensive than the fossil-fuel option.[77] Ranges reflect judgments about likely probability distribution of unit costs and allow for variability in fossil-fuel prices. For most technologies, unit cost is likely to fall over time, although as given technology comes up against constraints and extends beyond its maximum efficient scale of production, costs could rise. Adapted from reference 9 under the terms of the click-use licence.

year by 2050 in any successful scenario of economic development. Therefore the costs of mitigating climate change need not disrupt the prospects for the achievement of economic prosperity in the developing world or the maintenance of it in rich economies, even if costs rose to the upper end of the range.

The review also suggests that climate change is the greatest market failure of all time and recognises that policies taken to reduce climate change could also affect other externalities (eg, health, social, and environmental damages) and therefore potentially have lower costs than would first seem.[9] For example, studies in China typically show that the benefits from reducing health-damaging air pollution more than offset the costs of action for carbon dioxide reductions up to 10–20%.[74–76] However, the review only considers air pollution with respect to transport (and this is not costed in the model). It does not include the costs of injuries and physical inactivity, or the benefits of a more pleasant urban environment. Motorised traffic has contributed to the increased numbers of people who are unfit and overweight, while dangerous streets and sprawling cities all discourage active travel. This form of path dependency is difficult to include in such an economic analysis. The review notes that transport is fairly price insensitive and the IPCC also states that, for transport, financial instruments are likely to decline in effectiveness with higher incomes. Thus other policies to encourage modal shift will be needed, such as urban redesign, promotion of active travel, and more investment in improved and affordable public transport.

The standard economics approach differs from a public-health approach in that it places greater value on harms to the rich than to the poor. The review states "The price of marketed goods and services, as well as the hypothetical values assigned to health and the environment, are typically higher in richer countries than in poor countries. Thus in these models, a 10% loss in the volume of production of an economic sector is worth more in a rich country than in a poor country. Similarly a 5% increase in mortality."[9] In view of the consistently greater harms in low-income countries and among low-income groups, the Stern review increases the economic costs of climate change by a quarter to produce the 20% figure that is the upper bound for the effects of climate change on GWP. However, from a health perspective, the effects could exceed that level and the arguments for action are likely to be even stronger than Stern presents.

There is a growing body of experience of promoting the development and use of low-carbon technologies. The scale and direction of current policies fall substantially short of what is required, but we are not starting from zero. The unit cost of a range of greenhouse-gas abatement energy technologies compared with the cost of fossil fuel technologies is shown in figure 4. The abatement costs, expressed in pounds sterling per tonne of carbon, are shown in table 2. Some approaches (but certainly not all) could have negative costs—ie, they lead to economic benefits because they are expected to become cheaper than the fossil-fuel options they displace or because of the savings in fuel arising from energy efficiency.

	Minimum	Maximum
Domestic energy efficiency	–300	50
Service-sector energy efficiency	–260	50
Industrial energy efficiency	–80	30
Transport energy efficiency	Probably negative	Needs to be assessed in detail
Large CHP	–190	110
Micro CHP	–630	–110
Onshore wind	–80	50
Offshore wind	–30	150
Marine (wave and tidal)	70	450
Energy crops	70	200
Solar photovoltaics	520	1250
Nuclear	70	200
Carbon sequestration	80	280

CHP=combined heat and power.

Table 2: **Carbon abatement costs in pounds sterling per tonne of carbon (2020)**[77]

The financial resources for climate change mitigation can be generated through national policies to favour the development and use of low-carbon alternatives to fossil fuels. Policies so far have focused on ways of improving the cash flows of private investments in the alternative sources. Three kinds of policies have been pursued in the OECD economies.

The first policy involves pricing carbon directly, either through a carbon tax, as in the Nordic countries, or through a marketable permit or so-called cap and trade system, as with the EU permit-trading scheme. Which is the best approach is often disputed. With a carbon tax, the level of emissions is determined ultimately by the effects of the tax on the choice and use of fuels; if emissions reductions remain too low, the tax can be increased. For cap and trade, the amount of carbon emissions permitted determines the price; the main difficulty is that the emission permits are often subject to political manipulation, which can lead to emissions being too high and a collapse in the carbon prices, as happened initially with the EU scheme.[78] However, a well-designed scheme could allow organisations flexibility in how they meet targets, guarantee a cap in emissions, and offset any increased costs of energy to poor people. The cap and share proposal[79] suggests that governments could share out emissions allowances equally to all their adult citizens who could elect to sell them at the current market rate to, for example, a bank or post office, from which they would be purchased by companies introducing fossil fuels into the economy.

The second policy involves raising the prices paid for the outputs of low-carbon energy technologies, exemplified by the Renewables Obligation in the UK, the feed-in tariffs in several EU countries, and the renewable energy portfolio standards in a growing number of US States.

Finally, the third policy involves reducing the private costs of investment through tax credits; government finance for research and development (R&D) and demonstration projects; tax credits for the incremental costs of commercialising the technologies; financial rewards for technological developments, and subsidising the costs of providing supporting infrastructure (as is the practice in all OECD countries, although to varying degrees).

Notwithstanding the much-discussed shortcomings in their scale and structure (eg, the UK Renewable Transport Fuel Obligation[80] has been criticised for encouraging the destruction of the rainforest through imports of palm oil[47]), such policies have several accomplishments to their credit: the portfolio of proven technological options for addressing climate change has widened appreciably to include the full range of renewable energy and energy-efficient technologies; conversion efficiencies have been improved; costs have been reduced; and there is fertile ground for discovery and innovation.

Other approaches could contribute to mitigation, such as tax incentives and procurement practices for purchase of energy-efficient vehicles, appliances, and buildings and the removal of perverse incentives and tax breaks for oil and coal exploration. Direct regulation, such as mandating carbon emissions of electricity production, energy-efficiency standards for buildings, vehicles, and appliances, and carbon-emissions standards for vehicles, can also make useful contributions to reducing emissions of greenhouse gas.

At the national level, policies will inevitably vary between countries, and often among regions within countries, as in the USA. This is not only because they are the product of local social and political concerns, lobbying, and what is fiscally and administratively feasible, but also because energy markets and regulatory arrangements differ greatly, ranging from high levels of state ownership in some countries to high levels of market liberalisation in others.

The returns to innovation are likely to be immense. Over the past 15 years, the costs of the low-carbon options have more than halved. The possibilities for cost reduction and efficiency improvements from innovation are far from exhausted, and even conservative assumptions point to the possibilities of reducing the costs of responding to climate change by several hundred billion pounds sterling a year. Up to now nuclear fission has accounted for the largest expenditure on R&D, although the proportion has been falling since 1985. Currently, around 40% of energy R&D is spent on nuclear fission and 10% on nuclear fusion.[73] More money must be spent on R&D for renewable energy sources.

There is a debate about how much innovation would be better stimulated by either carbon pricing or supporting R&D, but most analysis points to the desirability of using both categories of instruments. Most analysis also points to the desirability of supporting a broad portfolio of technologies. No technology offers a panacea: nuclear power is still largely limited to base-load electricity production; fossil fuels with carbon capture and storage offer more flexibility but, without developments in hydrogen as a transport fuel and for heating, will be limited to the markets for electricity. Biofuels can make substantial contributions to the markets for transport fuels, heat, and electricity, but will eventually be limited by the availability of land; and although intermittent renewables such as wind, solar (photovoltaic and thermal), wave, and tidal energy are together virtually unlimited in scope, they too will depend on the development of storage or hydrogen-using technologies at high levels of market penetration. Additionally, technologies that are more costly today, such as solar energy and decentralised forms of heat and power, hold too much promise to be ignored.

At the international level, there was progress at the G8 summit in June, 2007, at which G8 countries agreed in principle that it was important to move towards binding limits on carbon dioxide emissions with the aim of at least halving global emissions by 2050 as part of a UN process. Although reaching a binding international agreement on emission targets for greenhouse gas is essential, other important opportunities for progress could have been overlooked. For example, although the US federal government and some emerging economies have in the past rejected such agreements, they are willing—and, indeed, in the case of the USA are leading efforts—to develop and use low-carbon technologies and practices. A focus on policies that encourage this trend should lead to early agreement, which in turn could set the scene for a more comprehensive international framework via phase II of the Kyoto Protocol under the aegis of the UN.

Even though there are important steps low-income countries can take to reduce the rise in energy demand through such policies as supporting policies to promote active and public transport over the car, with current technologies and market mechanisms it is unrealistic to expect them to have a leading role in the widespread adoption of renewable energy technologies because of their high cost. Moreover, rising prices and reduced availability of fossil fuels in the future have the potential to increase poverty and impair public health if policies are not put in place to prioritise access to electricity for the populations of low-income countries.

The investment requirements in developing countries will be such that, as with conventional aid, resources provided by an expanded programme of international assistance will need to be coupled with those generated by policies in the countries themselves. There are several possibilities, as follows. (1) To support the expansion and improvement of facilities established so far such as the Global Environment Facility (GEF) and the Clean

Development Mechanism (CDM), which facilitate the transfer of resources to low-income countries for renewable energy technologies. The CDM needs improvement because it has been criticised for paying up to 50 times as much for the reductions in emissions as the costs alone would warrant and for paying for projects that provide little additional effect because they would have occurred anyway.[81] (2) To support, in addition, the establishment of the new financing facilities proposed in the World Bank's Investment Framework.[82] (3) To add to this framework a further facility to address the problem of emissions arising from deforestation, land clearance, and land degradation. (4) To use the finance provided under points 2 and 3 as a means of furthering climate change policies at the national level. (5) To establish institutional arrangements for involving scientists and engineers from developing regions in R&D and the demonstration of low-carbon technologies and practices. Such arrangements were first instituted five decades ago for the green revolution in agriculture, with considerable success.

The international community has been moving in these directions for some years. The GEF and its implementing agencies, for example, already have 15 years of investment experience, and there have been numerous other multilateral and bilateral endeavours. More recently the Global Bioenergy Partnership will "assist international exchanges of know-how and technology, promote supportive policy frameworks and identify ways of fostering investments and removing barriers to the development and implementation of joint projects".[83] Thanks to national policies so far, and to international investment, albeit on a still minor scale, a portfolio of low-carbon technologies is emerging, in developing as in the OECD countries. There is thus a good technological and institutional base on which to build future policies.

Population and greenhouse-gas emissions

As discussed in the first article in this Series, at its simplest, global emissions of greenhouse gas are a product of population, GDP per head, energy use per unit GDP, and greenhouse-gas emissions per unit of energy. This is an example of the $I=PA(E)T$ equation, where I represents the natural resources used or pollution generated; P is the population; A is the per-head output (affluence); E is energy use per unit economy, and T represents the natural resources used or pollution produced per unit energy (technology).

There are arguments for using the household rather than the individual as the unit of choice: there are substantial economies of scale at the household level, and over time the growth rate in the number of households could be greater than the population growth rate. Given that it is unlikely in the foreseeable future that per-head emissions of greenhouse gas can be reduced to zero, it is clear that the population must play a substantial part in determining global emissions of greenhouse gas and thus the rate and magnitude of climate change. In the near term, population growth will make a predictable contribution to the accumulation of greenhouse gases in the atmosphere, in view of the momentum of population growth.[84] However, in the longer term, different population trajectories could have a substantial effect on greenhouse-gas emissions. Bongaarts[85] concluded that 50% of the growth in global emissions of carbon dioxide from fossil fuels between 1985 and 2025 was due to population growth, according to the scenario under consideration. Over the next century there will be a major shift between more and less developed countries in the proportion of greenhouse-gas emissions, with less developed countries becoming responsible for most of the growth in emissions.[73] Although policies to reduce per-head emissions will have the largest effect in the short term, policies to accelerate the demographic transition and thus reduce population growth can have a major effect on greenhouse-gas emissions in the long term. Indeed, it has been said that the most cost-effective greenhouse-gas measure could be investment in making condoms and other simple birth-control technologies more widely available in populations wishing to limit their family sizes.[86]

Because of the high per-head emissions in more developed countries, any population growth there would have a disproportionate effect on greenhouse-gas emissions but, in view of rising per-head emissions in many middle-income and low-income countries, reducing population growth in these settings could also have a substantial effect. Thus, for example, a reduction of 1 billion people in the world population, each of whom were responsible for emissions of 1 tonne of carbon a year, could contribute to reducing carbon emissions by 1 gigatonne a year, the equivalent of those strategies advocated as stabilisation wedges. Of course, there are many other reasons to support programmes that address the unmet need for effective family planning, including the reduction of infant and maternal mortality rates and, probably, of reducing poverty.[87,88] The international family-planning budget is currently only 10% of that projected in 1994 to be required by 2005.[89] The need to address climate change is a further argument to increase funding to family-planning programmes and to improve education about effective family planning for disadvantaged populations and particularly women.

Finally, population growth is also a function of the level of education and development. A properly financed and incentivised clean-energy transition will stimulate education, create jobs, diminish disparities, and improve health and wellbeing; these factors can contribute to reducing population growth.

Role of the health community

In addition to continuing to work to reduce the current large unnecessary health burden from energy systems, the professional and academic health communities have appropriate roles to play in all three types of interaction between health and climate change, as follows. (1) Investigation of the effects of climate change on health will remain an important arena of research and is needed to assist in the establishment of the priorities for mitigating climate change in comparison with other societal needs. Additionally, the health community has an appropriate role in the promotion of activities to mitigate greenhouse-gas emissions, both at the institutional and clinical levels.[90] (2) Assessment and promotion of interventions to reduce greenhouse-gas emissions that also promote other health objectives (co-benefits) while avoiding negative effects are also important roles for the health community (webpanel 4).[91] (3) Finally, by adjusting its own priorities in recognition of the coming risks to health from the climate change to which we are already committed, the health community continues to best serve one of its primary purposes, promoting the public's health. Here, one of the major messages for the community to convey is the importance and effectiveness of reducing vulnerability in the most threatened populations.

See Online for webpanel 4

Addressing the energy needs of poor people, preventing dangerous climate change, and promoting health

The UN Framework Convention on Climate Change in 1992 called for stabilisation of greenhouse-gas emissions at a level to "prevent dangerous anthropogenic interference with the climate system".[92] However, it did not define what constitutes a dangerous level of greenhouse gases and inevitably such a concept is open to different interpretations and difficulties in settling on a specific concentration because of many uncertainties. One approach is to seek to keep greenhouse-gas concentrations below that concentration which might lead to certain thresholds being exceeded. These thresholds could be normative thresholds of social effects or thresholds that if exceeded might lead to instability of the climate system or some major element of it.[93] Examples include potential disintegration of the Greenland ice cap with warming above 1°C and disintegration of the west Antarctic ice cap with 2–4°C warming. A range of ecosystem effects occur with warming of 1–2°C. Additionally, the capacity of the oceans to absorb carbon dioxide declines as they warm. Given the serious nature of these events and the real possibility that the climate and natural systems could be more sensitive than is predicted from average values, it is necessary to keep warming to a minimum. The EU[94] has stated that temperature increases should be limited to 2°C. It has undertaken to pursue in international negotiations a reduction in 30% from 1990 levels of greenhouse-gas emissions by developed nations by 2030. However, the report indicates that greenhouse-gas concentrations must be kept well below 550 ppm CO_2e with stabilisation around 450 ppm CO_2e to have a 50% probability of keeping temperature increases to below 2°C, and that a 30% reduction is unlikely to be sufficient. To stabilise greenhouse-gas concentrations in this way will require global emissions to peak before 2025 and decline by up to 50% by 2050.

A CO_2e concentration of 455 ppm has now been reached,[15] and emissions are still rising. This means that past policy failures to reduce emissions and prepare for a low-carbon economy have probably already committed us to considerable harms from climate change. To prevent these harms from increasing, society should strive to keep concentrations as far below 550 ppm CO_2e as feasible. Although this target poses challenges, this series has shown that policies to reduce greenhouse-gas emissions through the increasing energy efficiency and use of renewable and other low-carbon or zero-carbon energy sources can benefit health substantially in the near term as well by mitigating climate change. Reduced consumption of red meat and dairy products in high-income countries would also reduce emissions from livestock and probably benefit health by reducing cardiovascular disease and, for red meat, bowel cancer.

Meeting the essential energy requirements of poor populations would contribute little to global emissions of greenhouse gas while substantially improving their health and wellbeing, even if derived from petroleum fuels.[95] The wide international inequalities in greenhouse-gas emissions will need to be addressed not least because developing nations are unlikely to accept their continued existence and, if the world's population had the same per-head emissions as, for example, the citizens of the USA, the consequences would be profound. For this reason the concept of contraction and convergence[96] has been proposed, which aims for equal per-head emissions over time. This aim requires choosing a stabilisation target and a date for convergence in per-head emissions between countries. Stabilisation at 450 ppm CO_2e and convergence by 2030, for example, would necessitate reductions of per-head emissions of 90% for many developed nations (around 95% for the USA). Illustrative emission pathways

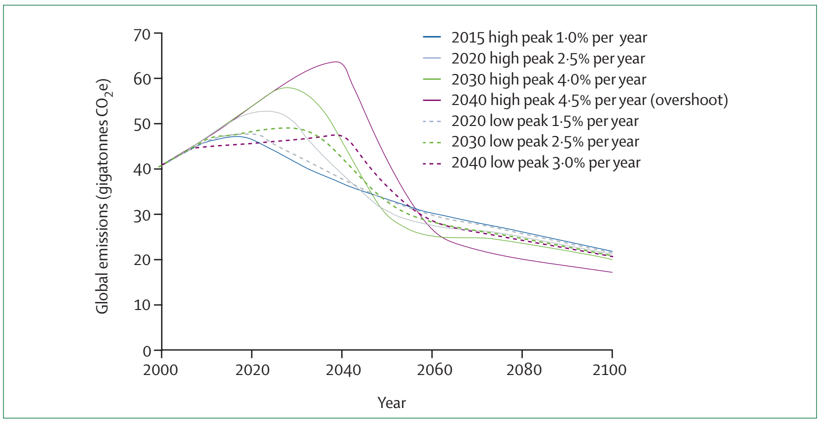

Figure 5: **Illustrative emissions paths to stabilise at 550 ppm CO_2e**[9,97]
Rates in key are maximum 10-year average rate of decline of global emissions. Delaying emissions cuts (shifting peaks to the right) means that emissions must be reduced more rapidly to achieve same stabilisation goal. Rate of emissions cuts is very sensitive to height of peak. For example, if emissions peak at 48 gigatonnes of carbon dioxide rather than 52 gigatonnes in 2020, rate of cuts is reduced from 2·55% per year to 1·55% a year. Adapted from reference 9, crown copyright.

to stabilise greenhouse-gas emissions at 550 ppm CO_2e are shown in figure 5.[9,97] To stabilise at lower levels would obviously require deeper cuts in greenhouse gases.

Although there are several technological options and policy levers, particularly with economic instruments, there are a number of barriers to change, including vested interests, political inertia, wide global inequalities, weak technology-transfer mechanisms, and gaps in knowledge. These factors will all need to be addressed if change is to be successfully implemented. The need to develop and implement policies that prevent dangerous climate change while addressing the energy needs of disadvantaged people constitutes one of the major public-health challenges of the current era. Concerted action will be required to bring together health professionals with sectoral specialists and policy analysts.

Health professionals are in an excellent position to affect policy through their individual commitment to the reduction of greenhouse-gas emissions, by promoting sustainable development policies within national health systems,[98] and by informing policies and practices in the private and public sectors. The health community also should re-emphasise to society at large the value of reducing vulnerability to environmental stressors in general, including climate change, through the traditional public methods, including better nutrition, education, health-care access, environmental sanitation, vaccination, and so on. Reducing background burden will have a major ameliorative effect on the realised burden from climate change: healthier people resist stressors of all kinds better than others. The health sector itself uses substantial energy and health professionals need to ensure that policies to reduce greenhouse-gas emissions in health facilities are implemented (webpanel 5).[99,100]

See Online for webpanel 5

Some of the greatest benefits to public health have been achieved through environmental interventions. Notable examples include the legislation and works programmes of the 19th century to improve water and sanitation in London, and the first Clean Air Act of 1956 after the London smog of 1952, which was followed in 1968 by further legislation. These major pieces of legislation responded to the urgent environment and health problems of the day. They both entailed major changes and required considerable resources to implement. From the perspective of the 21st century, it seems obvious that London needed a proper sewage system and cleaner air. Although it is difficult to make a formal analysis of the costs and benefits of the changes needed, there are surely few who would now think them unmerited or, indeed, who would consider them as anything less than vital steps in the improvement of public health.

The challenges relating to energy use today are no less urgent. As with the resurgence of infectious diseases (cholera, tuberculosis, and smallpox) in the urban centres of England in the mid 19th century and the pervasive industrial pollution of the mid-20th century, in this era of climate instability and emerging effects throughout the biosphere, public health must again become the focus for development. But the problems and solutions are now global, rather than local and national, in scale.

Throughout this Series we have presented evidence about the connections between energy use (or lack of it) and adverse effects on population health. Some of the pathways are straightforward, others are more complex. There are huge burdens of illness, mortality, and lost potential relating to lack of access to clean household energy for more than 2 billion of the world's population, large health effects from outdoor air pollution due to fuel combustion, substantial effects on workers in energy industries, and a growing crisis of global climate change stemming largely from the unrestrained use of fossil energy resources by the people living in the richer economies. Solutions to tackling both climate change and lack of access exist, given sufficient political will. If successful, the health dividend now and in the future promises to be very great indeed. The clean-energy transition can become the first, necessary, though insufficient, step toward sustainable development. It will be for future generations to judge whether we, who perceived the problems, had the vision and commitment to meet the challenge at its critical stage.

Conflict of interest statement

PRE declares that BP is represented on the Corporate Council of the Center for Health and the Global Environment at Harvard Medical School and pays an annual subscription. All other authors declare that they have no conflict of interest.

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