Energy and Health 4

Energy, energy efficiency, and the built environment

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Since the last decades of the 19th century, technological advances have brought substantial improvements in the efficiency with which energy can be exploited to service human needs. That trend has been accompanied by an equally notable increase in energy consumption, which strongly correlates with socioeconomic development. Nonetheless, feasible gains in the efficiency and technology of energy use in towns and cities and in homes have the potential to contribute to the mitigation of greenhouse-gas emissions, and to improve health, for example, through protection against temperature-related morbidity and mortality, and the alleviation of fuel poverty. A shift towards renewable energy production would also put increasing focus on cleaner energy carriers, especially electricity, but possibly also hydrogen, which would have benefits to urban air quality. In low-income countries, a vital priority remains the dissemination of affordable technology to alleviate the burdens of indoor air pollution and other health effects in individuals obliged to rely on biomass fuels for cooking and heating, as well as the improvement in access to electricity, which would have many benefits to health and wellbeing.

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

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The built environment includes the buildings in which people live and work, and the spaces and infrastructure in cities, towns, and villages. It is where most human activity takes place, where most energy services are used, and where many of the advantages and disadvantages of energy use arise.

The world is becoming increasingly urbanised. In 1950, only 30% of the world's population lived in urban areas; currently the proportion is almost 50%.[1] Net population growth of the next few decades will nearly all accrue in the urban centres of developing countries.[2] With urban and industrial development comes growing demands for energy and rising expectations of material goods.

This article analyses the connections between the built environment, energy, and human health. The global context is the need to ensure the adequate, equitable, and secure access to clean and safe energy for all individuals, while minimising greenhouse-gas emissions.

Key messages

- Global trends in urbanisation and industrial development will probably be a continuing major driver of increasing fossil-fuel use over coming decades
- Technological advances have a contribution to reversing raised greenhouse-gas emissions, but evidence of past trends shows even notable improvements in technological efficiency tend to be accompanied by increased, not reduced, use of fossil fuels—underlining need for instruments to promote decreased energy use or to decarbonise use
- Nonetheless, evidence indicates health benefits from improved energy efficiency—eg, in home environments and protection against temperature-related morbidity and mortality
- Shift towards renewable energy production will put increasing focus on cleaner energy carriers—electricity and probably hydrogen—which would have particular benefits for health in urban environments
- One particularly difficult challenge is to tackle lack of access to clean energy and dependence of many people in low-income settings on inefficient and inadequately ventilated burning of biomass for household energy needs

Energy efficiency—an important goal for health

Efficient use of energy is seemingly a very attractive means to reduce energy-related effects on the environment and health. To achieve the same services with less energy use should, in theory, reduce burdens on infrastructure, decrease occupational risks, lower costs, cut emissions of local pollutants and greenhouse gases, and lessen harmful exposures. Efficiency improvement also seems to have enormous potential: currently only 20–30% of the chemical energy of the fuel burned is typically transformed to useful work or heating (figure 1).[2]

Although behavioural factors have a part in such use, greater energy efficiency—ie, higher ratio of useful energy output to input energy—essentially means more efficient technology. In society, as efficiency rises, the direct

Key indicators

- Number or proportion of homes in low-income countries reliant on inefficient burning of biomass or coal for household energy needs
- Concentration of outdoor air pollutants, especially smaller particles (PM_{10} and $PM_{2·5}$), in urban centres
- Rate of mortality and morbidity related to combustion-derived air pollution, indoors and outdoors
- CO_2 emissions per dwelling
- Energy needed per dwelling to maintain essential fuel needs, specifically adequate heating and cooling

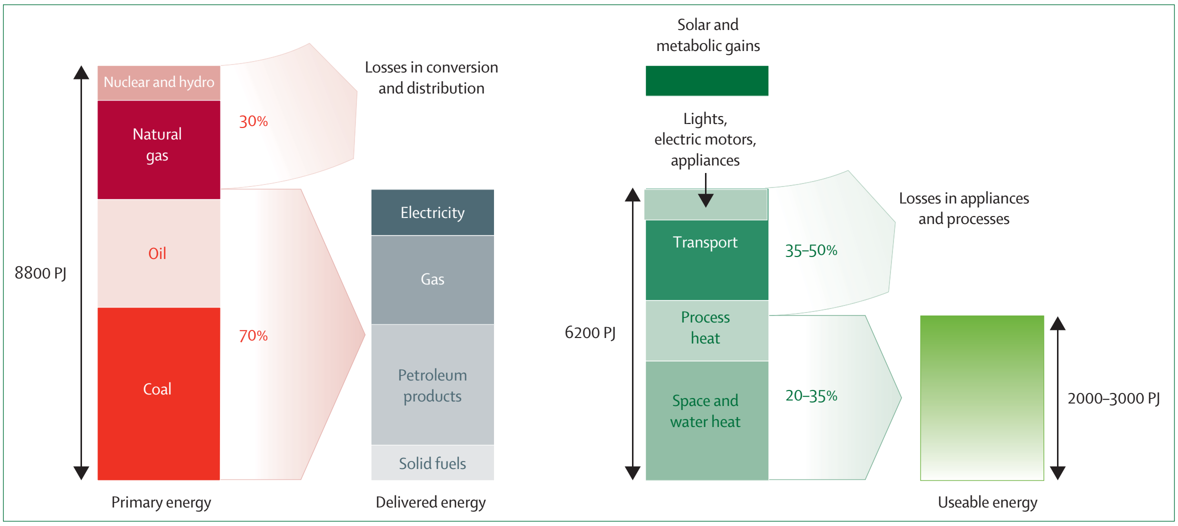

Figure 1: **Schematic of UK energy flow**[2]
1 petajoule (PJ)=10^{15} joules.

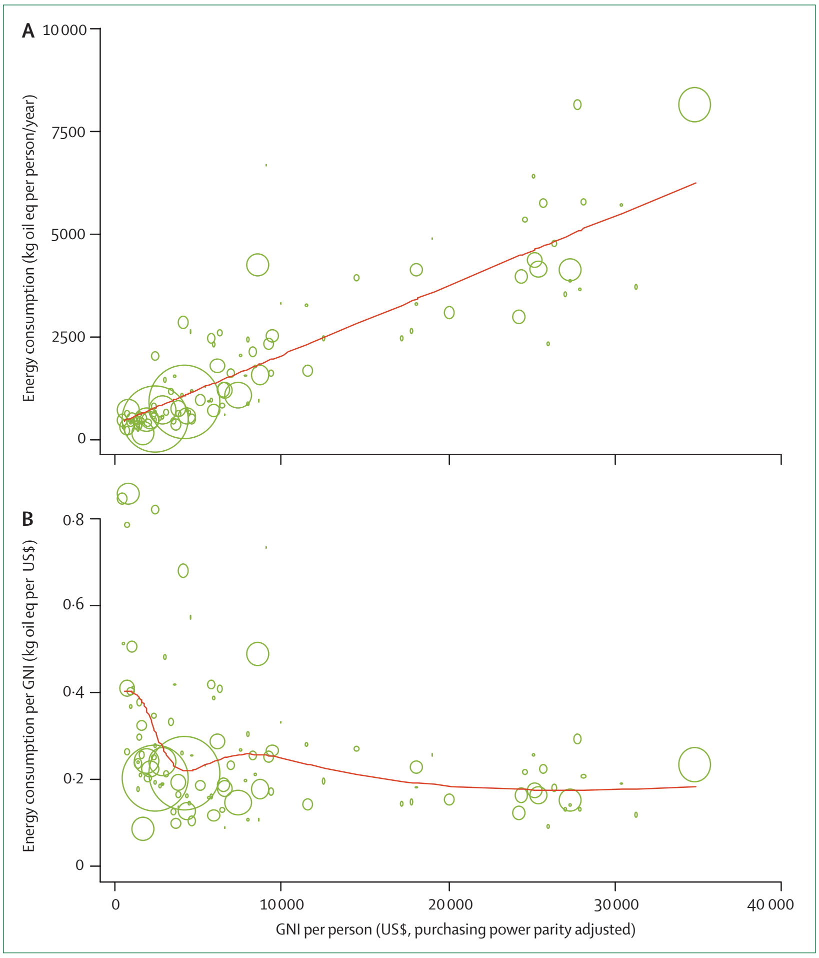

Figure 2: **Scatter plot of (A) energy consumption and (B) energy consumption per gross national income (GNI) *vs* per head GNI**
Graphs constructed from online data sources.[5,6] Symbol sizes are proportional to country populations. Kg oil eq=energy equivalent to that produced by combustion of kg of oil.

energy-related health effects of energy use tend to fall because of increasingly clean, often centralised combustion of fuels, and cleaner end-use technology—often accompanied, as wealth increases, by more effective systems and legislation for control of health-damaging emissions.[3] This pattern is the wealth-related risk transition described in the first article of this Series.[4] Emissions of carbon dioxide (CO_2), the dominant anthropogenic greenhouse gas, are also, in theory, reduced. But until now, and perhaps still into the future, an apparently immutable law of socioeconomic development has been that use of energy services grows at faster pace than improvement in efficiency. The net result is that richer societies, with generally cleaner energy use, also contribute most per head to overall energy use and consequently to CO_2 and other greenhouse-gas emissions (figure 2).[5,6] Until the evidence about its role in climate change, CO_2 was regarded an innocuous by-product of fossil-fuel combustion.

This association between wealth and energy signals a fundamental challenge for tackling climate change, and is an important reason why efficiency alone will not sufficiently reduce greenhouse-gas emissions without additional attention to the character of energy used. Without some form of direct control, increase in energy efficiency for an energy service often leads to substantially increased demand for the service, because of the lower price it creates per unit service. Vaclav Smil[7] provides several examples. The efficiency of street lighting in the UK increased 20-times between the 1920s and the end of the 20th century, from about 10 lumens per watt (W) for incandescent bulbs to about 200 lumens per W for low-pressure sodium lamps. Yet during the same period, the average intensity of street lighting also rose steeply, with the net result that lighting-related energy consumption per km of road increased 25-fold. In the

	Expected lifetime (years)
Building environment	
Urban plan	100+
Building	45+
Transport system	
Road/rail routes	100+
Motor vehicles	12–20
Energy generation	
Coal station	45+
Nuclear station	30–60
Gas turbine	25

Adapted from reference 8.

Table 1: **Expected lifetime of infrastructure**

transport sector, the internal combustion engine went through similarly advanced technological development during the 20th century, improving its mass-to-power ratio from 30 g/W in 1900 to about 1 g/W in 2000. Yet this change, along with other largely technological achievements, has allowed a spectacular rise in car ownership and in the yearly distances travelled by road. The changes in aircraft engines (from propeller, to turbojet, to turbofan designs) has been even more striking, with the most modern high-bypass turbofans (0·1 g of weight per W of power) making intercontinental travel almost routine—and at a rate of energy consumption per passenger-mile approaching that of some road vehicles. During the past 30 years, the theoretical energy efficiency of the UK housing stock has increased by 30%, although the net energy use has also increased by 30%. Of course, the effects of the different factors involved are difficult to separate, including price, efficiency, rising wealth, technological improvement, and investment in infrastructure.

These trends in individual pieces of technology add up to macroeconomic patterns (figure 2)[5,6] that are visible in historical trends. Over the 20th century, substantial improvements have been seen in global energy efficiency as shown by the ratio of energy use to gross national incomes (GNI). But energy consumption in total and per head has also risen greatly. Such evidence should not be interpreted as implying that energy efficiency itself is the key driver of increased energy use, but that efficiency gains typically have gone hand in hand with economic growth, rising expectations, social changes, and population increase. As the world becomes wealthier, energy-using devices are developed and deployed to fulfil our needs for productivity, recreation, security, comfort, and health. The important lesson is that if society wishes to lower energy-related emissions of greenhouse gases and other combustion pollutants, mechanisms are also needed to ensure that the full costs of energy use, including those related to damage to health and the environment, are reflected in choices made for individuals as well as society as a whole.

A second limitation on what energy efficiency can achieve, at least in the short term, is one of practicality. Urban layout, building structure, and the devices used in buildings typically have long lifespans of decades or longer (table 1)[8] and require substantial capital investment to replace.

Consequently, energy properties of the built environment include much inertia, and long lead-times are needed to achieve substantial change, apart from when there are opportunities for retro-fitting. But any attempt to adapt old buildings is often expensive and less effective than designing efficiency into new infrastructure. Moreover, new energy efficiency technology is also not always compatible with existing infrastructure: a wall cavity cannot be filled with insulation if no cavity exists. For many adaptations, the cost-effectiveness might seem unattractive without full account of environmental and health effects, and many households, companies, and institutions may have little incentive to make the necessary capital outlay.

Nevertheless, because of poor information and other barriers, major gains can be made for all societies in enhanced energy efficiency. Furthermore, many efficiency measures are actually cost-negative—ie, they save money. Thus, even though some of the potential energy savings will not be realised because of increased activity, energy efficiency comprises the major "low hanging fruit" in nearly all energy studies. Efficiency can be achieved in terms of urban structure and form, in building form and construction, and in energy-using appliances within buildings. The degree of planning, timescale for change, and capital investments needed vary substantially across these categories. Another important question for health in the built environment is the nature of the energy carriers (the fuels) used to deliver energy services. Cleaner forms of power generation, based on renewable or nuclear technology, could also favour the use of cleaner energy carriers, such as electricity and hydrogen, as the main modes of energy delivery that can reduce human exposures to health-damaging pollutants. The benefits of energy efficiency and of modal shifts in energy carriers will be considered in the final section of this article.

Before turning to specific aspects of the built environment, we should note that health systems themselves are substantial users of energy. For example, in 2001, the UK National Health Service (NHS) estate consumed an estimated 12 650 gigawatts per h of energy—about 0·8% of the total energy consumed in England and Wales.[9] This figure is almost doubled if other health-service buildings, including administration, are included. Additionally, NHS staff, visitors, and patients travelled some 25 billion passenger-km (about 3·5% of the national total), and if energy expenditure by the pharmaceutical industry is also taken into account, the energy consumption by the health sector could be between 3% and 5% of the national total. In terms of per head per year, this level of energy consumption is not far below the typical total energy consumption of a person living in Bangladesh. The health sector itself therefore has an important role in leading efforts to find and deal with energy issues.

Urban structure

Urban design and infrastructure has bearing on various aspects of energy use and health effects. First, it is an important determinant of energy use in buildings and of choices in transport (as described in the third article of this Series). Compact urban areas that avoid large distances between buildings and with few physical barriers are among the most important factors that could make the urban environment more conducive to physical activity, including walking and cycling.[10–12] Conversely, low-density urban areas tend to lead to poor access to public transport; high car use; and large heating, cooling, and lighting loads per individual. Lower urban density largely accounts for the much greater energy use per head in US cities than in European cities, for example. Separate but related debates have been made about the extent to which factors (such as socioeconomic mix) are important for social wellbeing. Thus, urban design and land-use choices are, in theory, determinants of energy demand, but even more important is that local environments could also affect health. As shown in article three of this Series, the main health connections are self-evident, and relate to effects on physical activity and weight management[13] (with their many physical and psychosocial benefits), as well as effects on injury risks, air pollution, and social cohesion, as seen in article three of this Series. However, specific epidemiological evidence about environmental interventions is comparatively limited, and is an area of much needed further research.[14–16]

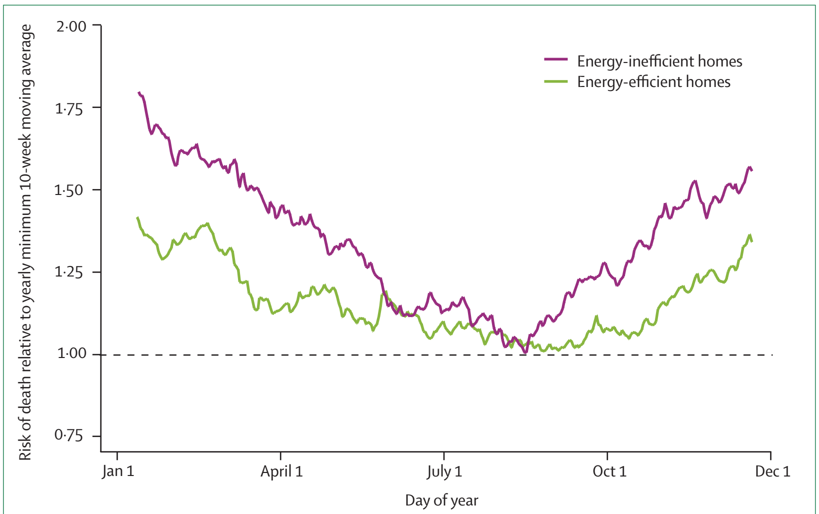

Figure 3: **Seasonal average variation in mortality in relation to energy efficiency of English homes**
Figure adapted from reference 37. Energy-inefficient homes are in the lowest quartile of standardised heating costs and energy-efficient homes are in the highest quartile.

High urban density also makes possible efficiency options of transferring by-product heat between power plants and buildings, and of having district heating systems. Such solutions could substantially improve the efficiency with which the energy from fuel is captured for useful work and heat. However, many local combined heat and power sources, particularly in areas of high population density, could have unwelcome effects on air quality compared with centralised generation and distribution of electricity, for example. The potential effects on health of such choices in energy delivery remain largely unquantified and are the focus of current research.

Urban density also affects two important human exposures that are under increasing attention in view of climate change and our apparently unbreakable dependence on motor vehicles—namely exposure to heat and outdoor air pollution. Outdoor temperatures within cities often exceed those of the surrounding countryside by several °C—a phenomenon referred to as the urban heat island effect.[17] The reasons relate to the high heat capacity of various elements of the urban environment, the reduced thermal radiation with sheltering by tall buildings, and lack of evapotranspiration because of the small number of trees and other plants;[17] heat generated by buildings, transportation, and other aspects of human activity can also add to ambient temperature warming. The magnitude of the temperature excess is variable, and depends on such factors as meteorological conditions and time of day. Its potential importance lies in the fact that, under climate change, the frequency, intensity, and duration of heat waves is expected to increase substantially,[18] with potentially important adverse effect on health,[19,20] as was shown, for example, by the heatwaves in Paris, France, in 2003[21] and Chicago, USA, in 1995.[22,23] Current urban environments could compound the risks because of the heat island effect, and also because of the way some buildings capture heat.

The available evidence does not yet allow precise quantification of the effect of the heat island effect on mortality during heatwaves. However, there is evidence that air conditioning protects against the risk of heat death,[22–26] and in consequence increased attention has been given to improved access to air-conditioned rooms as a health protection measure for heatwaves. Unfortunately, the energy demands of air conditioning are typically high, so its widespread use only adds to the problem of climate change. The alternative is to adapt urban spaces and buildings to use simpler, passive means of temperature control. Such options include: measures to increase shading from the sun (for example by planting trees);[27] provision for controllable ventilation during the day and high levels of ventilation at night; use of heavier-weight building materials; and improvement of insulation.[28]

The evidence for adverse effects of urban air pollution clearly shows that particle pollution in particular is responsible for a large global burden of mortality and morbidity.[29] Transport of air masses means that air pollution is not a uniquely urban problem, but it is predominantly urban because of the density of traffic and stationary sources in cities. Street canyons and other buildings in cities can also affect dispersal of pollutants and, thus, local pollutant concentrations. But in the context of climate change, interest is increasing in potential interactions between the weather and local air quality. Most notable is the possible effect on concentrations of summer ozone (which has well recognised adverse health effects)[30–33] because of the importance of temperature and sunlight to the air chemistry that leads to its formation. Although the effects of climate change on ozone are complicated, where the concentrations of precursors are high, ozone levels are likely to increase.[34] Ozone could have been responsible for an appreciable proportion of the deaths occurring during the 2003 European heatwave,[35,36] and the interaction of heat and ozone is an issue of increasing research interest, particularly to identify options for reducing the adverse health effects in the context of climate change.

Buildings: energy efficiency in the home

High-income countries

Because of the long lifespan of housing, in most countries, most of the existing stock (which typically accounts for more than a quarter of carbon emissions) predates modern energy and thermal comfort standards. In consequence, not only is it inefficient in energy use, but the cost and difficulty of space heating seem to contribute to ill health and even mortality risk, although research evidence remains notably sparse.[37] For example, a study of mortality patterns in England found that people who live in older, poorly heated homes of low-energy efficiency seem to be at increased risk of winter-related and cold-related death from cardiovascular disease. Even as a simple comparison, figure 3[37] shows the much larger seasonal fluctuation in mortality in people living in energy-inefficient homes than in energy-efficient homes.

The apparent conclusion, although still not formally tested through randomised controlled trials, is that more energy-efficient stock would reduce this mortality burden. In the UK, the yearly winter excess of deaths is typically between 20 000 and 50 000 deaths, mostly from cardiovascular causes.[38,39] Although exposures to the cold during outdoor excursions could be important in determining adverse health risks,[40,41] some research evidence and reasonable theoretical grounds suggest that the indoor environment is important as well. Thus, at least a theoretical rationale can be used to pursue energy efficiency on health as well as environmental grounds. Figure 4 shows the main connections between household energy efficiency and health.

A scheme to implement energy-efficiency improvements for low-income households in England has been running

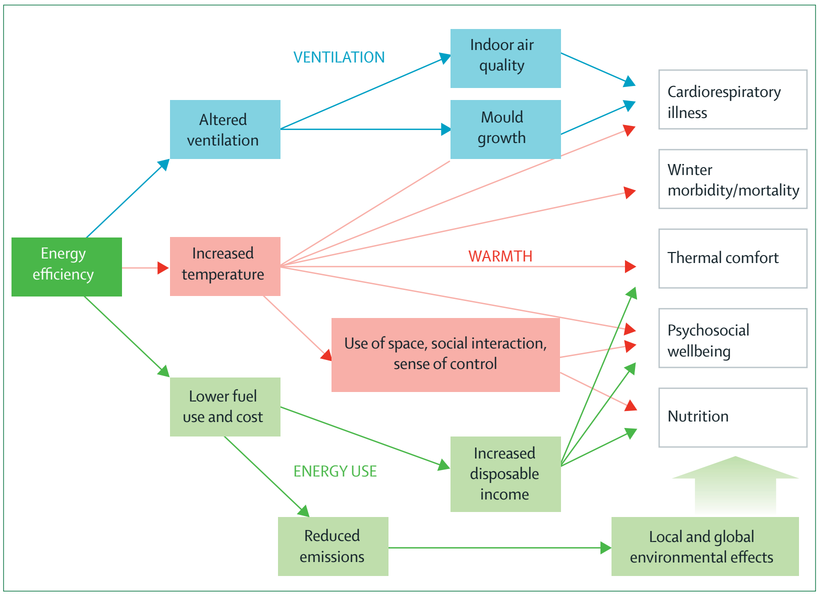

Figure 4: **Connections between household energy efficiency and health**
Note that energy reduction with improved efficiency depends on householder choice, and in practice many householders choose to use much of the benefit of increased efficiency as warmer homes in winter.

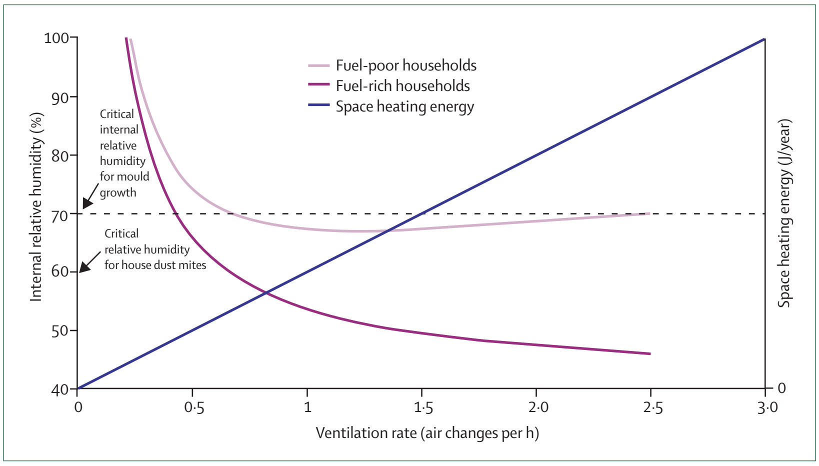

Figure 5: **Hypothetical relation between ventilation rates and indoor relative humidity for fuel-poor and fuel-rich households and energy to heat ventilation air[53,54]**
Magnitude of space heating energy depends on size of house and external climate.

over recent years, with the aim of tackling fuel poverty through packages of insulation (eg, loft or cavity-wall insulation, draught proofing) and heating system upgrades. Those improvements, which in theory reduce standardised CO_2 emissions and energy costs, have been shown to increase winter indoor temperatures (thus with probable benefits in terms of cardiorespiratory morbidity and mortality)[42] and to reduce normalised relative humidity, condensation, and visible mould growth.[43] Additionally, psychosocial benefits have been reported, consequent to improved thermal comfort, expanded use of space, increased privacy, and improved social interaction.[44] Notably, no evidence from this study of interventions in low-income households in England has yet shown that energy-efficiency improvements lower fuel consumption.[45] Evidence of a similar range of benefits has been obtained from one of very few randomised trials of energy-efficiency interventions. This New Zealand study[46] showed that insulation of existing houses led to positive changes to the indoor environment, improved self-rated health, self-reported wheezing, days off school and work, and reduced visits to general practitioners.

Improved energy efficiency could also affect health in other, largely unquantified, ways—through cost savings (potentially important for fuel-poor households—ie, those that need to spend >10% of household income on fuel), reduced emissions of air pollutants to the local environment, and (potentially) contribution to mitigation of climate change (figure 4). But another important benefit could arise from the replacement or refurbishment of old, inefficient, combustion appliances (boilers, burners, cooking stoves). Carbon monoxide (CO) is generated by incomplete combustion, and in high concentrations it can be rapidly fatal. There is suspicion that the occurrence of CO poisoning is under-diagnosed, and some debate—but no firm evidence—that chronic exposure to low-level CO can adversely affect cognitive function.[47–49] Although few surveys of indoor CO concentrations have been done, some surveys have found that peaks in indoor CO concentrations (up to or above 100 ppm [parts per million]) occur with non-negligible frequency. Whether measurable adverse effects exist from regular exposure to such levels, and how often appliances deteriorate further to produce acutely dangerous CO concentrations remains unknown.

Adverse effects could also result from improved energy efficiency if adequate measures are not taken to guard against reduced air exchange and if additional thermal insulation exacerbates rather than reduces summertime overheating.[50] The balance between adequate ventilation for health and reduced ventilation to minimise heat loss is probably one of the greatest challenges in the design and refurbishment of buildings to use low energy.[51,52] Figure 5[53,54] shows how the internal relative humidity and energy consumption changes with ventilation rate in a typical UK dwelling. Relative humidity is the main determinant of mould growth and the prevalence of house dust mites, both of which produce allergens. In northern European countries, a minimum air exchange rate of 0·5 air changes per h is recommended to protect against adverse effects.

For new buildings, the opportunities are much greater to incorporate energy efficiency measures from the outset. However, over the short term, new houses add to, or replace, only a small part of the total housing stock, and so can make only a modest contribution to efficiency gains. Moreover, with current constructions being predominantly of energy-intensive concrete, brick, steel, and glass, the construction of new buildings adds to carbon emissions. For example, production of a new house typically results in carbon emissions equivalent to 5 years' energy use. A large demolition and new building programme would, in the short term, contribute to climate change rather than mitigate it. However, most buildings undergo several phases of refurbishment during their lifecycle (windows, for example, tend to be replaced every 20 years or so), and for existing properties, the key is to take the opportunity of refurbishment to improve energy efficiency.[55]

Although energy efficiency is one of the key strategies to help meet energy needs, another strategy is the use of renewable energy generators integrated into the fabric of buildings. Renewable energy technologies such as solar thermal water heaters and photovoltaic solar panels can be located on the façade of buildings and generate solar electricity and heat. In many settings, the façade of a building can (in theory) generate nearly as much energy as the building requires, but the mismatch in time between generation and demand necessitates either expensive storage or a sophisticated trading of energy via a grid system. Furthermore, the capital cost of renewable technologies is high and the running cost low. This high capital cost is most often a challenge for vulnerable individuals, and a bigger divide between fuel-poor and fuel-rich homes (both between and within nations) can be envisaged in the future, unless policies are put in place to prevent this outcome. In the future, moving from a traditional centralised energy supply to a mixed system of local generation could, if not carefully managed, lead to new health and safety issues as home owners become responsible for energy-generating technology.

	Strength of evidence	Population group	Relative risk (95% CI)
Acute infections of lower respiratory tract	Strong	Children aged 0–4 years	2·3 (1·9–2·7)
Chronic obstructive pulmonary disease	Strong	Women aged ≥30 years	3·2 (2·3–4·8)
	Moderate I	Men aged ≥30 years	1·8 (1·0–3·2)
Lung cancer (coal)	Strong	Women aged ≥30 years	1·9 (1·1–3·5)
	Moderate I	Men aged ≥30 years	1·5 (1·0–2·5)
Lung cancer (biomass)	Moderate II	Women aged ≥30 years	1·5 (1·0–2·1)
Asthma	Moderate II	Children aged 5–14 years	1·6 (1·0–2·5)
	Moderate II	Adults ≥15 years	1·2 (1·0–1·5)
Cataracts	Moderate II	Adults ≥15 years	1·3 (1·0–1·7)
Tuberculosis	Moderate II	Adults ≥15 years	1·5 (1·0–2·4)

Data adapted from reference 57. Strong=many studies of solid-fuel use in developing countries, supported by evidence from studies of active and passive smoking, urban air pollution, and biochemical or laboratory studies. Moderate=at least three studies of solid-fuel use in developing countries, supported by evidence from studies on active smoking and on animals (moderate I=strong evidence for specific age/sex groups; moderate II=limited evidence).

***Table 2*: Health outcomes of indoor air pollution**

Low-income countries

In the first article of this Series, we referred to the 2 billion people without access to electricity and to the health burdens of indoor air pollution from household use of solid fuels in developing countries. These problems stem from poverty, but also pose some difficult technical problems of achieving reliable energy services at very low cost. They suffer from the same sort of social, economic, and political barriers that have long frustrated aspirations to ensure basic health needs are met for all people.

Lack of access to electricity and clean fuel lies behind many aspects of poor health and poverty in the developing world.[56] This situation is partly and indirectly due to energy's central role in supporting basic education and health infrastructure; but it also derives from direct effects of energy use at the household level and the quality of indoor air. Lack of access to clean household fuels and electricity has direct links to several Millennium Development Goals (MDGs).[57]

Household use of solid fuel, particularly biomass for cooking and heating, has perhaps the most direct link to the MDGs through its effects on the health of children and women. In unvented homes, the concentrations of health-damaging pollutants to which householders are exposed typically reach levels many times higher than those found in urban outdoor environments where health effects are well established.[58] The largest exposures occur to women, who are normally responsible for food preparation and cooking inside the home, and infants and young children who are usually with their mothers near the cooking area. Clear epidemiological evidence links these pollutant exposures to acute infections of the lower respiratory tract in children, which is the chief cause of child mortality in the developing world; to chronic obstructive pulmonary disease, especially in women; and (for coal, at least) to risk of lung cancer (table 2).[57,59,60]

Growing evidence indicates that these exposures are important risk factors for lung and other cancers (from biomass as well as coal burning), cataracts and other eye diseases, low birthweight and other adverse pregnancy outcomes, and tuberculosis. Increased risks for asthma and cardiovascular diseases are also suspected.

Although the epidemiological evidence base is growing rapidly and is consistent with animal and toxicological information, passive and active tobacco smoking studies, and outdoor air pollution epidemiology, household studies of solid-fuel air pollution have had important limitations in proving causality and quantifying the benefits of real interventions. These challenges include the residual confounding potential in the use of observational designs to study diseases that have many causes linked to poverty, which is also closely linked to use of low-quality fuels. Additionally, because of the problems in taking measurements in these settings, exposure-response associations have been difficult to determine. Thus, although links with several disease endpoints are becoming well established, what the effect of particular improvements might be is less clear. Therefore in a world in which public-health resources are extremely scarce for the populations that need them most, it has been difficult to argue that precious funds be diverted from the many other urgent health needs—such as vaccines, antibiotics, and food supplements to pregnant women—to improved fuels and stoves.

To address the need to provide high-quality evidence, the first randomised trial in air pollution to our knowledge was done in Guatemala.[60–62] Much more detailed outcome assessment was done than in previous studies, which probably confused many upper respiratory infections (which have little public-health effect) with lower respiratory infections (which are difficult to diagnose in field settings).[63] Furthermore, much more detailed exposure assessment was done than in any previous study. It showed decreases in blood pressure in women within 1–2 months after introduction of an improved chimney woodstove in a population using open wood fires for cooking.[64] The reduction in both systolic and diastolic blood pressure, which was seen in both cross-sectional and longitudinal analyses, substantially exceeded what is usually found in salt reduction studies. Furthermore, among infants in the intervention group, serious, physician-diagnosed, bacterial pneumonia, which is thought to have a higher case-fatality rate than viral pneumonia, was reduced by about 40%. This difference is less than that found in the observational studies, but indicates (without confounding) what can be achieved with a real intervention. No effect was found for infants with pneumonia who were positive for respiratory syncytial virus, which had been a study hypothesis on the basis of previous studies.[60]

This Guatemalan efficacy study, however, is only one in one region of the world. History has shown that, to have a substantial effect on policy, additional efficacy studies and large-scale effectiveness studies will be needed.

Although household stoves are the oldest of human combustion devices and have seen many innovations over thousands of years, the technology need to meet current expectations for protecting health is, perhaps surprisingly, not yet well developed in developing countries. In recent decades, several improved cook-stove programmes have been implemented by countries concerned mainly with improving fuel efficiency to protect local natural environments and to enhance energy services for the poor from existing biomass supplies. Even the largest and most successful of these, the Chinese programme, which was responsible for dissemination of 180 million stoves from the early 1980s to the late 1990s, did not have health as a major objective, although it reduced exposures to some extent through increased efficiency and use of chimneys.[65] No large-scale programmes and only a handful of small ones have yet addressed health directly by designing, testing, and monitoring their efforts in the context of exposure reduction or health improvement.[66]

One problem with existing improved stove technologies is illustrated by the Guatemalan trial, which is consistent with studies in several regions including China.[67] Even a well operating chimney stove only moves the smoke 1–2 m and does not actually reduce smoke emissions. Thus, pollution levels in and around the rest of the house do not change much and actual personal exposures do not reduce nearly as much as kitchen levels because people do not spend all day in the kitchen. The implication of this drawback for designing large-scale chimney-stove interventions needs to be explored, but the long-term message is clear: affordable, reliable stoves are needed that do not generate pollution in the first place.

Countries such as South Korea that transited from poor income to middle income in the past century before the rise in petroleum prices, simply switched household fuel use during this period from biomass to kerosene and liquefied petroleum gas,[68] products of the oil fuel cycle. By comparison with biomass (and coal), these fuels are very clean and efficient for household use. Unfortunately, however, current oil prices and associated uncertainties in the worldwide petroleum market make such a transition extremely difficult for most poor individuals in developing countries today. With even more large price rises in the past years, the price gap between biomass and these household fossil fuels has been widened further, probably driving some groups back to biomass, and greatly straining the budgets not only of households but also of the many governments, including those of India and Indonesia, that highly subsidise such fuels.

This widening price gap, however, also provides an opportunity to develop biomass-based stoves and fuels that have improved combustion and thus do not produce pollution at all. Several technical approaches seem attractive in this regard, most of which involve means to assure good secondary combustion. Such technologies probably cannot be developed at costs comparable to those of the cheap stoves found in the poorest households at present, which are often nearly costless, but would seem able to operate in the gap between these and the now quite costly fossil alternatives. Over time, as the market operates, economies of scale develop, technology improves, and the evidence needed to promote societal assistance grows, perhaps even the poorest groups could be served.

Although most people at risk of exposure to indoor air pollution live in rural areas of the world's poorest countries, this risk is increasingly becoming a problem for poor urban dwellers, a trend that will probably increase with the urban transition. Additionally, the effect on health of household fuel use go beyond indoor air pollution and affect the household economy, women's time and activities, gender roles and relationships, safety and hygiene, and the local and global environment.[57] For example, half the worldwide wood harvest has been estimated to be used as fuel. Furthermore, in some settings, poor families spend more than 20% of their disposable household income on biomass fuel (compared with 9% in the UK for household expenditure on housing fuel and power), or devote more than 25% of total household labour to wood collection. These additional benefits to improvement in the household fuel cycle relate to other MDGs, as seen in the first article of this Series.

Transition to clean energy

The contrast in the energy needs and priorities of rich and poor countries highlights a central tension that has been referred to earlier in this Series: in health terms, the poorest populations would gain from improved access to electricity and other modern energy sources, yet improved, access to energy also means increased consumption and potently increased emissions of greenhouse gases.

The solution lies not only in international agreements about equitable CO_2 emissions targets, but also in technology transfer—rich countries helping poorer populations to adopt clean energy technology (clean in terms of health-damaging pollutants and CO_2 emissions), thereby in part modifying the conventional pattern of environmental risk transition associated with economic development.

Clean technology is usually more expensive than conventional technology, and if not widely affordable in high-income countries, it is far less affordable (and generally a much lower priority) in less developed countries. Thus, to counter potential economic barriers, technology transfer should also carry transfer of resources, and on a large scale. Because of the often scarce international aid available, such resources should be deployed in ways that meet local public-health and development priorities, yet evidence indicating the most cost-effective deployment is unclear. Nevertheless, almost all measures aimed at reducing greenhouse-gas emissions and accelerating the transition to newer energy technology will probably have beneficial effects on outdoor air quality, particularly in urban settings.[3] This aim is a major public-health argument for greenhouse-gas mitigation policies, and the potential for benefit is theoretically greatest in some of the cities of low-income to middle-income countries that are undergoing rapid economic development.

Co-benefits to outdoor air quality of greenhouse-gas reductions and clean energy technology

Estimation of the effect of greenhouse-gas mitigation policies on air quality is an uncertain process. However, several theoretical calculations have been attempted, on the basis that good evidence now exists about the associations between outdoor air pollution and health, and reasonable models of the contribution of emission sources to air pollution concentrations. One such study was done by Cifuentes and colleagues,[69,70] who developed scenarios for Mexico City, Santiago de Chile, Sao Paulo, and New York, using air pollution health effect factors appropriate to every city. They found that the adoption of readily available technology could lead to appreciable reductions in premature deaths, chronic respiratory disease, and person-days of work loss or other restricted activity—illustrating, in semiquantitative terms, at least, the principle that immediate co-benefits to health could accrue from efforts aimed at the control of greenhouse-gas emissions. However, such studies can only be indicative. The effects of control policies are infinitely complex to characterise in reality, and innumerable assumptions need to be made about health effects of air pollution and their reversibility. Nevertheless, it is quite reasonable to expect substantial benefits of this kind, even if uncertain in magnitude. Standard scoping methods for such analyses are also now being developed.[71]

Cleaner energy carriers

Similar arguments about health effects arise in relation to a switch towards cleaner energy carriers. While oil, coal, and gas supplies decline as primary energy sources, current forms of energy delivery will be gradually substituted by other, often cleaner, energy carriers, including electricity, and potentially biofuels and hydrogen. The switch to electricity and hydrogen in particular would have a substantial effect on the local emission of air pollutants in urban environments.

Electricity is a high-quality and very versatile energy carrier, which is almost certain to have an increasing role in the delivery of energy in future. In 1900, electricity accounted for only around 2% of energy consumption, whereas it is around 30% currently,[7] which largely stems from its many advantages. For individuals with access to mains supplies, electricity is instantly available, effectively free of emissions at the point of consumption (apart from low-frequency electromagnetic fields), and it can drive a wide range of electric and electronic devices which are integral to modern living. Although any possible health effects of low-frequency electric and magnetic fields are unclear, no conclusive evidence so far has indicated substantial health risks: such risks are certainly low by comparison with those associated with emissions from the combustion of carbonaceous fuels. Death and serious injury from electrocution in the home remain uncommon:[72] figures from the Office for National Statistics show that in England and Wales, for example, 20–50 deaths per year were recorded from accidental electrocution in 1994–2003. Of course, combustion-related emissions, even from distant power stations, contribute to background levels of air pollution, so the full benefit for health of a modal shift towards electricity will depend also on the extent to which it is generated by clean technology.

The chief disadvantages, however, are that electricity can be comparatively inefficient to generate and transmit, and cannot be directly stored. Fluctuations in demand therefore need a (networked) supply that can cope with variations from base-load to peak-load within very short time-periods. However, such a coping mechanism is theoretically achievable even with largely renewable electricity generation by use of efficient demand management systems, time-of-day pricing, and other load-levelling techniques, used in concert with energy storage, including pumped water, thermal inertia, and other technology. However, most such storage holds energy at much lower density than fossil fuels (table 3).[73]

The impetus to develop hydrogen as an energy carrier is based on several desirable properties. By mass, its combustion liberates much more energy than conventional hydrocarbon fuels (although it is not as dense an energy store as fossil fuels, even when highly compressed, table 3); transport of energy through pipelines could be more efficient than through electric power lines (>1500 km of hydrogen pipeline in Europe already exists); it can be ignited with air in a normal internal combustion engine; it can be turned into electric current in a fuel cell; and, with some technical constraints, it can be stored.

Perhaps its most important benefit, however, is that its combustion with air generates water vapour with very little pollution other than some mononitrogen oxides (NO_x), and no CO_2. There are no substantial pollutant emissions from hydrogen fuel cells. Although water vapour is an important greenhouse gas, the burning of hydrogen as a fuel at ground level will not affect water vapour concentrations in the atmosphere in ways that could materially influence the Earth's radiative balance.

Hydrogen is not a primary fuel, however. At present its production is dominated by processes that depend on conventional energy sources. Reformation of natural gas

	Weight (kJ/kg)	Volume (MJ/m³)
Conventional fuels		
Crude oil	42 000	37 000
Coal	32 000	42 000
Wood	12 500	10 000
Synthetic fuels		
Hydrogen, gas	120 000	10
Hydrogen, liquid	120 000	8700
Hydrogen, metal hydride	2000–9000	5000–15 000
Methanol	21 000	17 000
Ethanol	28 000	22 000
Thermal energy (low-quality)		
Water (100–40°C)	250	250
Rocks (100–40°C)	40–50	100–140
Iron (100–40°C)	Roughly 30	Roughly 230
Thermal energy (high-quality)		
Rocks (eg, 400–200°C)	Roughly 160	Roughly 430
Iron (eg, 100–40°C)	Roughly 100	Roughly 800
Mechanical energy		
Pumped hydro, 100-m head	1	1
Compressed air	..	Roughly 15
Flywheels (steel)	30–120	240–950
Electrochemical energy		
Lead-acid	40–140	100–900
Nickel cadmium	Roughly 350	Roughly 350
Lithium ion	700	1400

Table adapted from reference 73.

Table 3: **Energy density of various forms of energy storage**

(heating with steam to about 1000°C), the most common form of production, yields about 11 tonnes of CO_2 emissions per tonne of hydrogen. Hydrogen is seldom used as an energy fuel, but is an important chemical product used mainly in the production of ammonia for nitrogen fertilisers and in the conversion of heavier crude oils to lighter fuels. Its worldwide production, currently about 50 million tonnes a year, is rapidly growing. Whether it has a substantial role as a fuel mainly depends on two issues: whether it can be economically produced without substantial greenhouse-gas emissions; and whether the technology and systems can be developed for its safe storage and use in everyday life.

See Online for webappendix

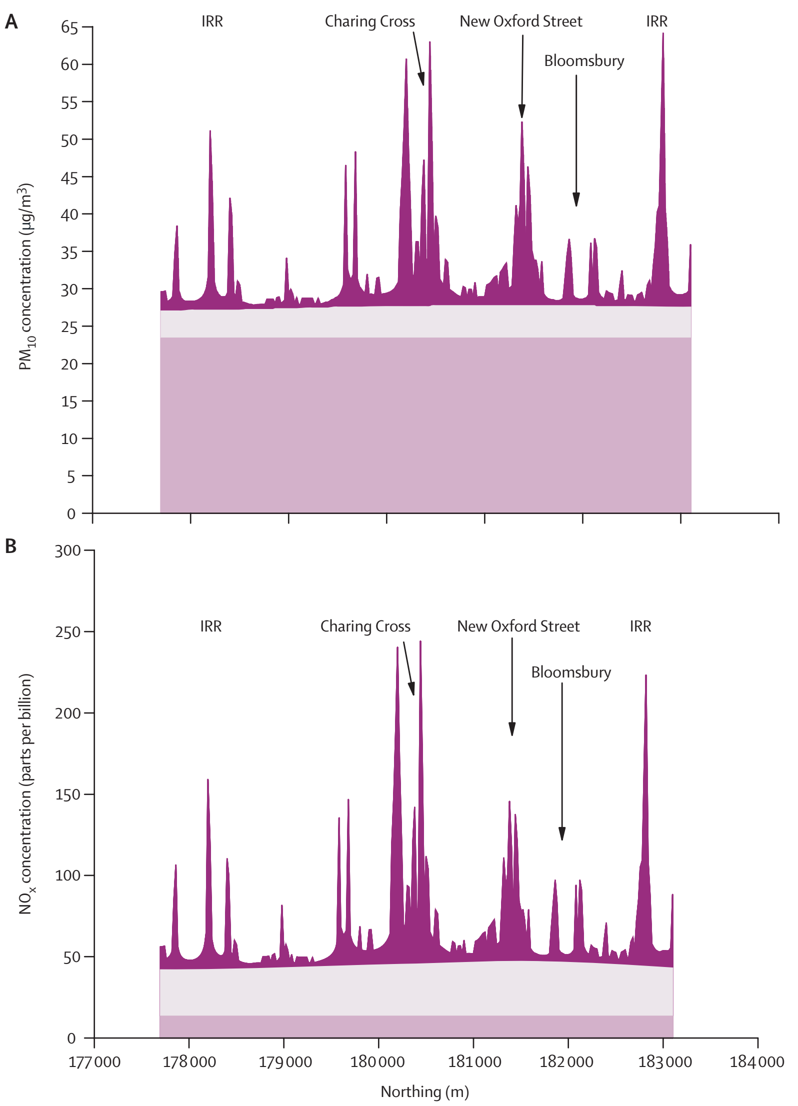

***Figure 6:* Sources of air pollution along south-north transection across central London, UK (London Congestion Charging Zone)**

Figure based on an emissions-dispersion model. Location of selected main roads in central London are indicated to show local peak in pollution levels. Light purple=long-range transport (rural background). Light grey=urban-area sources. Dark purple=local (mainly transport) emissions sources. IRR=inner ringroad of central London. NO_x=oxides of nitrogen. Northing=distance north on the British grid system.

Hydrogen could be produced from electrolysis of water in off-peak periods by use of electricity from nuclear power or other low-carbon generation. Norway already produces hydrogen for the fertiliser industry by electrolysis using hydroelectric power. In future, substantial production could occur by direct thermochemical processes, by use of the heat of various designs of high-temperature nuclear reactors.[74,75] The economics are not yet favourable, but the equation could alter as oil prices rise and closer attention is paid to the environmental and health costs of burning fossil fuels.

The second issue has important technological hurdles. Hydrogen's low boiling point (–253°C) and density (0·09 g/L under atmospheric pressure and ambient temperature) mean that it has to be stored under high pressure, at very low temperatures, or by adsorption onto alloys (eg, titanium and iron or magnesium and nickel). Hydrides concentrate hydrogen almost as effectively as storing it in liquid form, but over time the efficacy of this process wanes. The buoyancy of hydrogen means that it is rapidly dispersed from a leak, but it is flammable at a low concentration in air and its ignition energy is an order of magnitude lower than for petrol or methane (0·02 mJ *vs* 0·24 mJ).

With appropriate technology, however, the risk of a combustion accident is probably no greater than for petrol or natural gas. Hydrogen could be delivered to buildings via a reticulated network of pipes, and its use has been successfully shown in buses and cars, and even in trial aircraft. Technological barriers and cost mean that its use will initially be restricted, probably to selected vehicle fleets (eg, bus fleets served by garages with the necessary technology adaptations) and small-scale stationary plants. The case for hydrogen use as a fuel for energy in buildings is particularly unclear, because an effective electricity grid can deliver controlled power directly without need to generate hydrogen as an intermediate carrier. Nonetheless, hydrogen as a fuel is familiar from the days of "town gas" (which was largely a mixture of hydrogen and CO) produced from coal before the arrival of natural gas, and it can be added to the existing (natural) gas network in concentrations up to about 20% without need for special adaptation. Despite some technical hurdles, the potential contribution of a hydrogen economy to a cleaner, healthier environment seems attractive, even if the economics are currently unfavourable. Mark Jacobson's assessment[76] of the effect of converting all US road vehicles to using hydrogen fuel cells suggests that 3700–6400 lives per year could be saved.

London case study

The webappendix[77–90] provides a case study illustration of the possible effect on air pollution and health of policies aimed at greenhouse-gas emissions controls and possible switch in energy carriers in London. The calculations are entirely hypothetical, based on very broad indicative scenarios, and compare theoretical futures with the status quo. The scenarios include changes to the fuels (energy carriers) for transport, changes in buildings-related energy use, and assumptions about patterns of vehicle use. The hypothetical experiments assume immediate and complete implementation of broad policy objectives, and are thus somewhat artificial because, among other assumptions, no account is taken of the underlying trends in (for example) technology, building regulations, and vehicle numbers, which mean that the future energy-related emissions in London would be very different in the future even without these scenario changes. And such substantial shifts as these scenarios suggest would in reality take time to achieve. Nonetheless, the air pollution modelling used is reasonably well developed; and the use of life-table analysis based on published exposure-response associations is an established approach to estimate the health effects.[79]

The results (webappendix) should be interpreted not as precise estimates but as signposts of the air-pollution-related health gains in the short term. They indicate modest but worthwhile short-term co-benefits of bold (but theoretically achievable) policies aimed at reducing greenhouse gases, irrespective of the (unquantified) long-term benefits through limiting climate change. Although the legitimacy and detail of these scenarios can be challenged, they provide two important observations.

First, action is necessary on many fronts—in buildings, transport, human behaviours, power generation—if the net result is to achieve the necessary reduction in CO_2 emissions. Even with the fairly bold objectives set out in these scenarios, which imply quite substantial change, the combined effect on overall CO_2 emissions is still only part way toward the required medium-term reduction in greenhouse gases for a city in a high-income country.

The second observation is the interdependence of cities and regions in terms of air pollution. In the scenarios, we assumed changes in emissions in London only, and not in the surrounding region. But as figure 6 shows, regional air quality has an important bearing on air quality in London.

For particle pollution (PM_{10}) in particular, a high proportion of the concentrations arise from long-range transport of pollutants from outside London, much of it transported from the near continent, including France and the low countries—although such secondary pollutants could be less relevant for health than primary particles generated locally. The local urban-area sources of particles in London contribute a modest addition to PM_{10} levels, and vehicle emissions along the road network account for the local spikes. Thus, action in London alone is necessarily limited in the extent to which it can reduce overall particle pollution: more substantial reductions will require collective action in neighbouring countries and beyond, including changes to cleaner modes of power generation and industrial energy sources. Concentrations of oxides of nitrogen (webappendix), which are largely traffic-related, more closely related to local sources.

Conclusions

As with so many aspects of the energy debate, the factors that can and do have bearing on future policies for the built environment are innumerable. However, the mechanisms to include proper assessment of the health costs and benefits of those complex choices so far have not been developed and are often not sought. Scientific evidence is always imperfect, but for many questions, such as the effects of indoor air pollution, the evidence of health links is already strong and partly quantified; for others, such as the effects of energy-efficient homes, the evidence is meagre; yet even in this area, such available evidence amounts to a persuasive case that health and environmental goals are generally served by broadly the same policy course. What is needed to help embed this understanding into policy action are large studies that can provide a sound basis for assessment of cost-effectiveness, taking account of multiple direct (immediate-term) and indirect health links. These studies will be complex, but the questions are important. The energy policy implemented for urban environments, and for international development, must surely be one of the current priorities for public health.

Conflict of interest statement

We declare that we have no conflict of interest.

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