4 Energy and Health

Convening Lead Author (CLA)

Kirk R. Smith (University of California, Berkeley, USA)

Lead Authors (LA)

Kalpana Balakrishnan (Sri Ramachandra University, India)
Colin Butler (Australian National University)
Zoë Chafe (University of California, Berkeley, USA)
Ian Fairlie (Consultant on Radiation in the Environment, UK)
Patrick Kinney (Columbia University, USA)
Tord Kjellstrom (Umea University, Sweden)
Denise L. Mauzerall (Princeton University, USA)
Thomas McKone (Lawrence Berkeley National Laboratory, USA)
Anthony McMichael (Australian National University)
Mycle Schneider (Consultant on Energy and Nuclear Policy, France)
Paul Wilkinson (London School of Hygiene and Tropical Medicine, UK)

Review Editor

Jill Jäger (Sustainable Europe Research Institute, Austria)

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Executive Summary

Despite providing significant benefits for human health, energy systems also negatively affect global health in major ways today, causing directly perhaps as many as five million premature deaths annually and more than 5% of all ill-health (measured as lost healthy life years). Air pollution from incomplete combustion of fossil fuels and biomass fuels is by far the single major reason that energy systems negatively affect global health, although ash, sulfur, mercury, and other contaminants in fossil fuels also play a role. Effects on workers in energy industries are the second biggest health impact globally.

The largest exposures to energy-related air pollution occur in and around households, particularly in developing countries where unprocessed biomass (wood and agricultural wastes) and coal are used for cooking and heating in simple appliances.

This chapter does not focus on differences in impacts among alternative energy systems that have *minor* impacts on global health; rather, the focus is on the most significant impacts of energy systems on health. The important positive impacts of energy systems on health are mostly addressed in Chapter 2.

Given the importance of avoiding climate change, there is secondary focus on the ways that mitigating climate change through changes in energy systems might achieve important health improvements: co-benefits.

Unless major policy interventions are introduced, energy systems are expected to continue contributing significantly to the global burden of disease for years to come.

Household air pollution: GEA estimates for 2005 put the burden of disease caused by household air pollution at about 2.2 million premature deaths annually. These deaths occur mainly among women and young children in developing countries because they receive the highest exposures to household air pollution from cooking and heating with solid fuels. Although the fraction of households relying on solid fuels is slowly declining, the absolute numbers are still rising among the world's poorest populations.

The only way to ameliorate this health risk is through encouraging as many households as possible to use clean-burning gases and liquids made from biomass or petroleum fuels while initiating widespread promotion of new generations of advanced combustion biomass stoves. These stoves reduce biomass emissions to nearly the level of emissions from clean fuels, by using small blowers and other technical innovations.

Outdoor air pollution: Outdoor air pollution from incomplete combustion and other emissions from fuel use is also an important health risk globally. GEA estimates that it was responsible for some 2.7 million premature deaths in 2005. Outdoor air pollution affects not only urban areas, but many regions between cities, due to long-range transport of pollutants. Dominant sources of outdoor air pollution include combustion of fossil fuels in industry and transportation. In addition, poor household fuel combustion is a significant contributor to outdoor pollution in many parts of the world, for example South Asia and China, which means that the goals for clean household energy and general ambient air pollution are linked. GEA scenarios project the magnitude of the improvement that could be achieved with (1) implementation and enforcement of strict emissions controls, (2) universal access to clean cooking fuels, and (3) shifting of energy to non-combustion energy sources and efficiency.

Occupational health impacts: Occupational injuries and diseases, particularly in biomass and coal harvesting and processing (such as coal mining and transport), are the next most important impact on health from energy systems. Only strict adherence to international norms for worker health and safety can blunt this impact. Despite substantial gains over the past 50 years at some energy-related workplaces, health and safety systems do not exhibit best practices in many countries. The advent of novel nano- and other engineered materials for advanced solar and other energy systems potentially pose risks to workers and the public that need to be carefully investigated before widespread deployment to avert health impacts before they occur.

Nuclear power impacts: Unlike biomass and fossil fuels, nuclear power systems are not a significant source of routine public health impacts globally, although they often garner considerable public and policy concern. This said, reprocessing facilities release significantly larger amounts of radioactivity than power reactors and uranium mining leads to considerable environmental effects and health risks to workers. Average radiation doses to workers in nuclear power industries have generally declined over the past two decades, but tend to be concentrated in workers under less regulatory control. For nuclear power facilities, as with large hydroelectric facilities, the major health risks lie mostly with high-consequence but low-probability accidents. These risks are difficult to compare to the impacts that occur day-to-day. (See Chapter 14 for more discussion of nuclear accidents).

Energy efficiency and health: Although energy efficiency is usually found to be the best overall first strategy to improve the sustainability of energy systems, there can also be downsides if done without care. This has been seen, for example, in programs to improve the energy efficiency of buildings without considering the impacts on indoor air quality of reducing ventilation or use of improper materials.

Climate change, energy, and health: Climate change to date, to which energy systems are a significant contributor, is starting to have an important impact on health, perhaps exceeding 200,000 premature deaths annually by 2005, more than 90% among the poorest populations in the world. It is expected, however, that the health burden due to climate change will rise under current projections of greenhouse gases and other climate-altering pollutants (CAP) and background health conditions in vulnerable populations, which are largely in developing countries. Well over 20 million people along the vulnerable coastal regions of Bangladesh, Egypt, and Nigeria are estimated to be at risk of inundation from a one-meter sea level rise, not accounting for inevitable population growth. Other health impacts from climate change include the effects of extreme weather events, heat waves or sustained periods of extreme heat, malnutrition, spreading infectious diseases, and resource-related conflicts.

Protecting the climate system and improving health: There are a number of opportunities to reduce the current burden of disease while also reducing the pressure on global climate. Some relate simply to reducing energy use and its associated health and climate impacts through efficiency improvements and increased use of non-carbon based fuels, particularly renewable energy sources. Others, however, take advantage of the relatively high health and climate risk per unit emission posed by targeting specific short-lived greenhouse pollutants produced by energy systems, in particular black carbon and the precursors to ozone such as methane. Some of the energy-associated and health-damaging pollutants, such as sulfate and organic carbon particles, however, have cooling characteristics that create potential trade-offs between health and climate goals when controlling certain sources.

Overarching concepts: Per unit of useful energy, the health and climate benefits of emission reduction interventions rise with the fraction of incomplete combustion; and, also per unit of useful energy, the health benefits of emission reduction interventions rise as the combustion is closer to the population, increasing the proportion of emissions inhaled by the population.

From a health standpoint, in addition to reducing risk factors such as air pollution and climate change, there is equal importance to reducing vulnerability by improving background health conditions, particularly among the world's poor. Meeting the Millennium Development Goals (MDGs) as soon as possible will be critical, and bringing modern energy services to the world's people living in poverty is a necessary, if not sufficient, condition in doing so.

4.1 Introduction

Humanity requires energy to bring the benefits of health care, adequate food, education, protection against the elements, and the many other activities of society that enhance population health. On the other hand, dirty, dangerous, and environmentally disruptive energy supplies can lead to disease, injury, and premature death that is significant on local and global scales. Health impacts have thus been a major consideration in the promotion of some types of energy supplies and the avoidance of others.

Energy services provide important direct health benefits; for example, refrigeration preserves food and allows storage of vaccines. Energy for lighting enables health clinics to operate after dark. Energy for heating and cooling helps avoid heat stroke, hypothermia, and other health impacts of extreme conditions. It also improves general quality of life. These benefits are described in detail in Chapter 2. The lack of sufficient energy services, therefore, can be considered a health risk. However, whereas the impacts of lack of energy access are discussed elsewhere in the report, this chapter focuses on the health consequences of the energy society *does* use.

Two principal categories of risk lead to human health impacts associated with energy systems: risks resulting from routine operation (e.g., air pollution, occupational accidents) and risks from low-probability, high-consequence events (e.g., accidents at nuclear power plants and dams). Although the former category has the greatest impact on health year in and year out, the risk of major, if infrequent, events creates uncertainty and unease. Even as society seeks to limit such risks, there is sometimes a disconnect between calculated risk and perceived risk, the latter being influenced by the dread of disastrous, though rare, events associated with energy systems.

In addition to the public at large, many workers in the energy sector, especially in low-income countries, also bear health burdens from the world's energy supply systems. Although the total burden (mortality and morbidity) is larger in the public as a whole, the risk per person is usually greatest among workers, raising equity issues.

Within the general public, the health impacts of energy systems are also distributed inequitably. Not surprisingly, people living in poverty bear a disproportionate burden due to, for example, reliance on poor-quality combustion in households and living in the polluted areas of cities. They suffer more both because of their higher exposures and because of their greater vulnerability and co-risk factors, such as malnutrition and poor access to health care. The health effects of climate change also burden the poorest and most vulnerable populations disproportionately.

As with the environmental impacts presented in Chapter 3, the largest health impacts globally from energy systems are associated with the combustion of carbonaceous fuels, whether fossil or biomass. Chapter 3 presented the patterns of pollutant emissions from energy systems across the world and the resultant ambient air pollution levels. These are inputs into an assessment of health impacts but are insufficient by themselves. Firstly, there are substantially different types and magnitudes of health impacts from different types of pollutants. Secondly, health impacts are not a direct function of emissions or environmental concentrations but of human *exposure* to them. For instance, pollution over the ocean may cause impacts on marine ecosystems and the climate but no appreciable impact on human health because no one is there to breathe it. On the other hand, a relatively small amount of pollution emitted inside households may have major impacts on human health, but a small effect on ambient (outdoor) pollution levels. The exposure implications of different emissions sources has come to be termed the "intake fraction" – that is, the fraction of the material emitted to which the population is actually exposed (Bennett et al., 2002). This can vary by three orders of magnitude among energy systems and thus is crucial when considering health effects. Thus, no one-to-one relationship between the rankings of impacts in Chapter 3 and this chapter exists, even when the same sources and pollutants are considered (see Box 4.1).

In simple combustion situations, such as household stoves and small boilers in developing countries, combustion is far from complete, thus releasing a significant amount of the fuel carbon in products of incomplete combustion (PICs). These include a range of toxic compounds, such as carbon monoxide (CO), polyaromatic hydrocarbons (PAHs), benzene, and formaldehyde. Even when burned under excellent conditions, fossil fuels vary in quality. Some supplies contain significant toxic contaminants, such as sulfur, ash, and mercury, which are released in large amounts unless emissions are controlled after combustion. Finally, even when burned completely without any release of contaminants, carbon dioxide (CO_2) from fossil fuel use is the primary source of greenhouse gas (GHG) emissions, which threaten health through climate change. In general, consideration of climate change aside, health damage of all sorts is greatest with solid fuels, intermediate with liquid fuels, and least with gaseous fuels.

Health impacts from energy supply systems do not stem solely from the final conversion step – the power plant or automobile, for example. A common framework for evaluating the environmental and health implications of energy systems is the fuel cycle, which starts with harvesting of the raw fuel and proceeds through processing, transport, perhaps more than one conversion stage, and through to final waste disposal. In addition, there may be important impacts from the construction as well as the operation of facilities, together called "life-cycle assessment" (LCA) (see Box 4.4). Although the majority of health risk is usually exerted at the final conversion stage, a full understanding and comparison of energy systems requires such LCAs.

There is essentially no human endeavor that does not affect and is not affected by both health and energy in some way. The importance of and knowledge about the connections, however, vary dramatically. Here in the limited space available, we must focus only on the largest and most well understood of these relationships and thus set a fairly conventional system boundary for most of our analysis, i.e., energy supply systems.

As in the World Energy Assessment (Holdren and Smith, 2000) this chapter is organized by spatial scale, starting with what happens inside

Box 4.1 | Intake fraction

Health impacts of airborne and other pollutants depend on the level of exposure to the population of concern, which in turn depends not only on the amount and toxicity of emissions, but also on the proximity of the emissions to the population. Thus, if no one is downwind to breathe it, a pollutant released far from populations may not affect health significantly, while a pollutant released in the direct proximity of people can have a major effect, even if it is released in relatively small amounts. The metric used to compare such situations is called "intake fraction" (iF) which, for airborne pollutants, is simply the amount inhaled by the population divided by the amount released (Bennett et al., 2002). The difference between major categories of pollution can be several orders of magnitude, as illustrated in Figure 4.1.

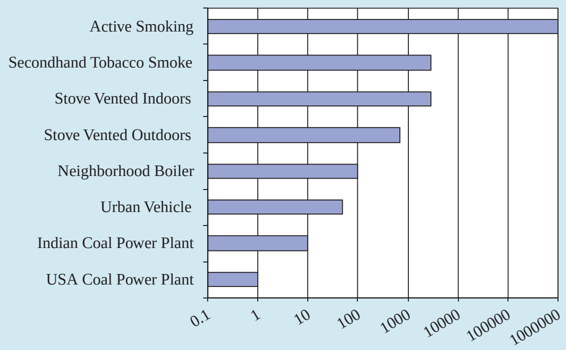

Figure 4.1 | Approximate intake fractions for typical sources of air pollution. Expressed as grams of pollutant inhaled for every tonne emitted. Thus, about one gram per tonne (one in a million emitted) is breathed by someone downwind of a typical power plant in the USA, while about 3000 grams are inhaled per tonne released indoors from a stove. Source: data from Smith et al., 1993.

Note that the iF for active smoking is 1.0 (one million grams inhaled for every million emitted): by definition, all the released pollutant is breathed in. At the other end of the iF spectrum in this figure are remotely sited US power plants, where only one millionth of what is released is breathed by someone. For pollutants released indoors, iFs are a few thousands per million, by comparison, while outdoor neighborhood sources range in between. The iFs vary by local situations, of course; for example, for indoor sources they depend on ventilation (Nazaroff, 2006). In cities, the iF of traffic pollution tends to be larger for bigger cities because the pollution is carried across the breathing zones of more people on its way downwind (Marshall et al., 2005). iF is generally used for primary pollutants, i.e., those actually emitted, and it must be supplemented by other analyses when addressing secondary pollutants, e.g., particles created downwind from sources emitting gases such as sulfur dioxide (SO_2).

The large difference in iFs across pollutant categories goes a long way toward explaining why relatively small amounts of pollution in the form of cigarette smoke or smoke from indoor cookfires can have such significant health impacts compared to the much larger amounts of pollution released from outdoor sources.

households and workplaces, moving to community and regional impacts, and ending with health risks from global changes due to energy use. In addition, we take up some special topics, including the health impacts of the nuclear fuel cycle, emerging technologies, and energy efficiency. Throughout, we start with a summary of what is known about health impacts today and then describe how these might evolve under different pathways of energy supply. As impacts on climate are a central theme throughout GEA, we end with a discussion of the potentials for "co-benefits," i.e., ways in which the evolution of energy systems can be directed to simultaneously achieve climate and health protection.

4.2 Household Energy Systems

4.2.1 Key Messages

- Human exposure to health-damaging air pollution from household combustion of fuels is widespread, affecting about 40% of the world population, and larger fractions in most developing countries.
- Women and children are likely to bear the largest share of the health risk burden from these exposures. According to GEA estimates in Chapter 17, household use of solid fuel for cooking resulted in 2.2 million premature deaths, or 41.6 million DALYs (disability-adjusted life years), in 2005, from exposures around the households.[1]
- Although only gaseous fuels and electricity offer truly clean performance, an emerging set of advanced biomass stove technologies

1 The most authoritative source of such estimates is the international Comparative Risk Assessment (CRA) which is part of the Global Burden of Disease Project. An extensively revised edition of the CRA is planned for publication in 2012, which will have updated authoritative estimates of the use of household solid fuels by region and the associated burden of disease as well as exposures and burdens from outdoor air pollution. These estimates are the most useful available for global policy because they are done across a range of risk factors, both environmental and other, in a consistent fashion. Thus they provide reliable information about the relative importance of interventions to improve health across sectors with minimal concern about differential assessment methods. Unfortunately, the updated CRA results were not available before GEA was completed but are scheduled to be available on the World Health Organization website in 2012: www.who.int/healthinfo/global_burden_disease/en/index.html.

provides intermediate performance that is more affordable and nearly as clean. More research and development is needed, however, to assess the field performance and acceptance of these stoves in different parts of the world, as well as the development of quantitative international standards for performance.

- Poverty and education deficits are likely to further exaggerate exposure potentials for vulnerable groups. To help meet the Millennium Development Goals (MDGs), opportunities to include household fuel and consequent air pollution issues in the mainstream public health agenda should be identified.

4.2.2 Background

A great majority of people living in poverty in developing countries have limited or no access to modern energy services, including access to electricity and modern fuels for cooking. As discussed in Chapter 1, GEA estimates that in 2005 about 2.8 billion people, mostly in the least developed and developing countries, relied on solid fuels such as biomass (wood, agricultural residues, and animal dung), charcoal, and coal for cooking and other household energy needs. Solid fuels in these households are often used in inefficient, poorly vented combustion devices, which results in the bulk of the fuel energy being emitted and wasted as toxic products of incomplete combustion. Further, the use of traditional stoves in small and poorly ventilated kitchens – in close proximity to household members on a daily basis – leads to exposures that are significantly detrimental to the health of family members, particularly to women and children, who spend the most time in or near the kitchen. Very young children are especially at risk, as they receive some of the highest exposures during vulnerable periods of growth. The scale of the exposures (spread across many countries), the complexity of the exposure situation (with multiple household-level determinants influencing frequency, duration, and magnitude of exposure), and the limited availability of data on exposures and health outcomes have resulted in a somewhat belated recognition of this risk factor as a major contributor to the disease burden at the global, regional, and national scales. Health impacts surrounding this risk factor are thus often neglected in global energy discussions.

With persuasive evidence for health impacts from the Comparative Risk Assessment (CRA) exercises conducted by the World Health Organization (WHO) (WHO, 2002), new, revised estimates of the burden of disease are being prepared, and an increasing body of scientific literature indicates substantial co-benefits for health and climate change from household energy interventions. This section provides an overview of patterns of household fuel use across world regions; concentrations and exposures experienced within household micro-environments; linkages between exposures and select health outcomes; and selected intervention options that are available and/or are being evaluated for broader application within countries (Household fuel systems of developed countries are not elaborated in this section but are discussed in Section 4.9 in the context of energy efficiency).

4.2.3 Patterns of Household Fuel Use in Developing Countries

Hundreds of demographic surveys conducted in developing countries, especially over the last decade, have collected information on household fuel use. According to a recent United Nations Development Programme review (UNDP, 2009), some 129 countries have data available on fuel use, including access to modern fuels and fuels used for cooking (see Table 4.1 and Figure 4.2). India and China together account for nearly half the global population that uses solid fuels for cooking (27% and 25%, respectively); sub-Saharan Africa also accounts for a significant share. Wood is the predominant type of solid fuel used, although in many surveys the distinction between wood, woodchips, and agricultural residues is not clearly made. Among developing countries generally, nearly 40% rely on modern fuels; however, in the poorest, least developed countries, gas use is uncommon. Use of other fuels is concentrated in certain countries, e.g., charcoal in sub-Saharan Africa, coal in China, dung in India, kerosene in Djibouti, and electricity in South Africa.

Accurate information on fuel use at the national and regional scales is a critical input for calculating the attributable burden of disease. Traditionally, the risk estimates from epidemiological studies have

Table 4.1 | Number of people relying on solid and modern fuels for cooking for all developing countries, least-developed countries, and sub-Saharan Africa.

	Number of people relying on solid fuels (millions)			Number of people with access to modern fuels (millions)
	Traditional biomass	Coal	Total	
Developing Countries	2564	436	2999	2294
LDCs	703	12	715	74
Sub-Saharan Africa	615	6	621	132

Notes: Based on UNDP's classification of developing countries, and the UN's classification of least developed countries (LDCs). There are 50 LDCs and 45 sub-Saharan African countries, with 31 countries belonging to both categories. Traditional biomass includes wood, charcoal, and dung. Wood includes wood, wood chips, straw, and crop residues. Modern fuels refer to electricity, liquid fuels, and gaseous fuels such as LPG, natural gas, and kerosene.

Source: data estimated by UNDP, 2009 for 2007.

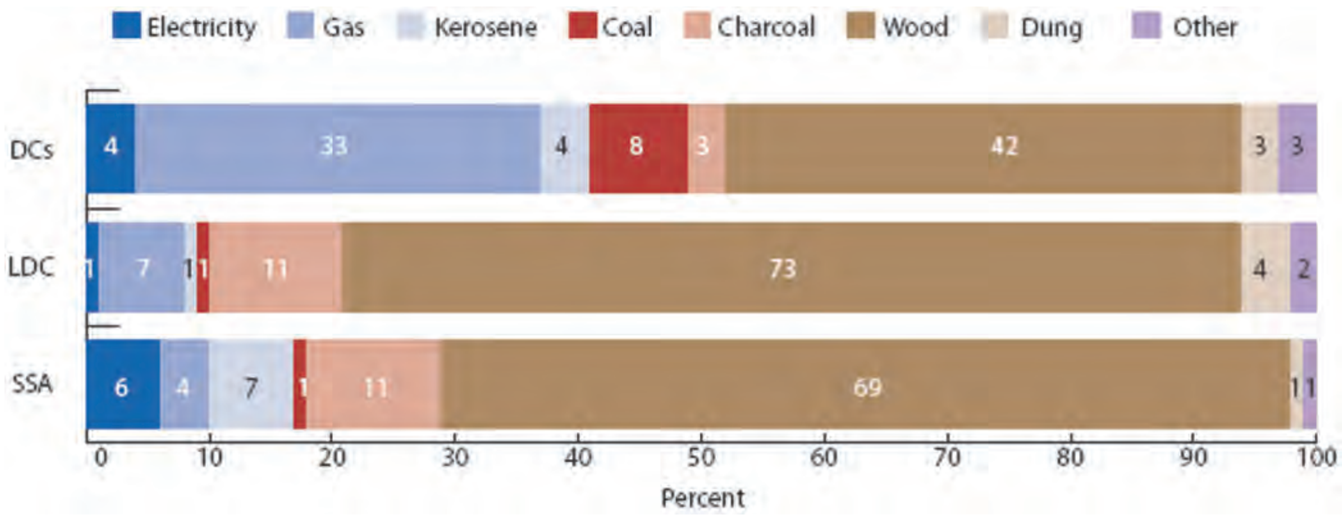

Figure 4.2 | Share of population relying on different types of cooking fuels in all developing countries, least-developed countries, and sub-Saharan Africa. Source: data estimated by UNDP, 2009 for 2007.

Notes: Based on UNDP's classification of developing countries (DCs), and the UN's classification of least developed countries (LDCs). There are 50 LDCs and 45 sub-Saharan countries (SSA), of which 31 countries belong to both categories. Gas includes natural gas, LPG, biogas, and ethanol. Kerosene includes kerosene and paraffin. Coal includes coal dust and lignite. Wood includes wood, wood chips, straw, and crop residues. "Other" includes missing data, "no cooking in the house," and other fuels.

been based on whether solid fuels are used for cooking or heating (WHO, 2002).[2]

Socio-economic factors significantly influence household fuel choice. In most countries with per capita incomes under US$1000, household fuel demands account for more than half of the total primary energy demand for cooking and heating; in contrast, such demands account for less than 2% of total primary energy use in industrialized countries (UNDP, 2000). As per capita incomes increase, households switch to cleaner, more efficient energy systems for their household energy needs, i.e., they move up the "energy ladder" (Hosier and Dowd, 1987; UNDP, 2000). With technological progress, the income levels at which people make the transition to cleaner modern fuels has fallen. However, availability of cleaner fuels at the national level does not guarantee availability of supply in rural areas (Masera et al., 2000), due to issues related to transport, reliability of supply, and socio-cultural preferences. Moreover, in every poor country the income disparities between rural and urban people are large, with most people in rural areas pursuing subsistence livelihoods. Household fuel generation, distribution, and consumption are thus closely related to the overall status of energy, environment, and development in the respective countries.

2 Only recently has it also been possible to estimate the exposure-response relationships for a few important diseases at exposure levels typical for populations using solid fuels for cooking. In addition, estimates of household exposures across major populations have been done. These will be available in the new CRA. See Footnote 1. The estimates in GEA, however, are based on the traditional approach: yes-no epidemiological relationships in which the average difference in disease between people living in polluted and less polluted households has been determined based on cookfuel type.

Several household factors directly influence patterns of human exposure to cooking fuel smoke, which occurs both inside and around households using poor combustion. Fuel type, kitchen location, use and maintenance of stoves, household layout and ventilation, time-activity profiles of individual household members, and behavioral practices (such as where children are located when cooking is being done) have been shown to influence pollution levels and individual exposures. Countries with low gross domestic product (GDP) also typically experience greater gender inequities in terms of income, education, access to health care, social position, and socio-cultural preferences, all of which could potentially influence exposures for vulnerable groups, such as women and children.

Geographic variables can also significantly affect pollution intensity and duration. Extreme temperature differentials between seasons, rainfall, altitude, and even meteorological factors (such as wind speed, wind direction, and relative humidity) could determine whether fuels are used for both cooking and heating, as well as whether they are affecting aerosol dispersion and/or deposition. Patterns of vegetation (e.g., tropical rain forests vs. scrub) could contribute to household decisions on seeking alternative energy sources. Easy availability of wood or other biomass at little or no cost is likely to encourage continued use, especially among people living in poverty.

Although the available literature does not allow a detailed attribution of exposures to each of these variables, these can be expected to make varying contributions and should be considered while creating local or regional profiles of the exposure situation. A schematic showing the potential determinants is shown in Figure 4.3.

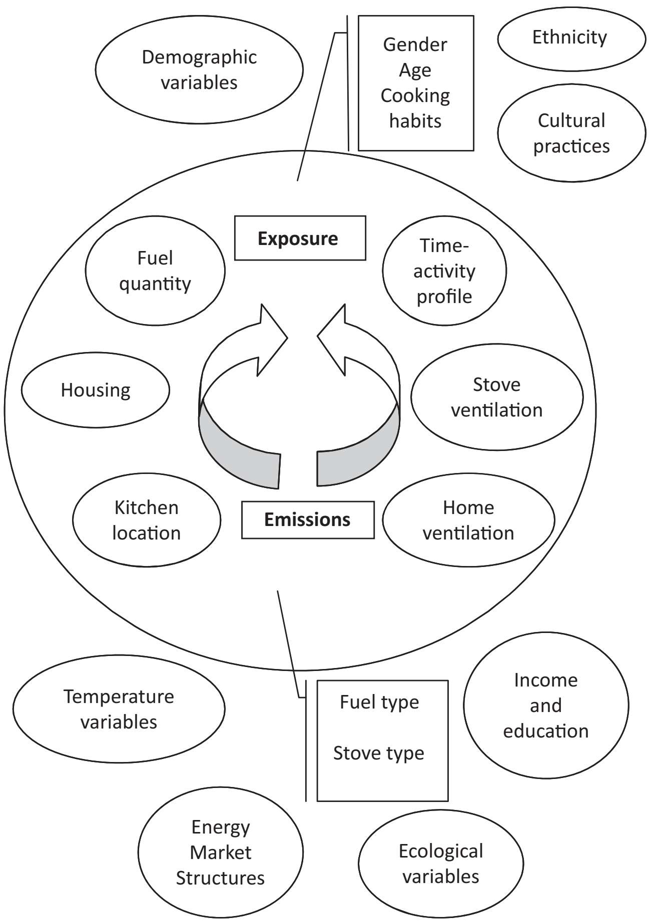

Figure 4.3 | Macro and micro-environmental determinants of exposure to solid fuel smoke.

4.2.4 Emissions from Combustion of Household Fuels

A majority of households in developing countries using solid fuels for cooking burn them in poorly functioning mud or metal stoves or use open pits, usually without a chimney or other arrangement to vent the smoke from the area. Under ideal conditions, complete combustion of carbon would produce only CO_2 and water. However, virtually all traditional ways of burning household biomass fuel emit substantial quantities of PICs, since conditions for the efficient combustion of these fuels are difficult to achieve in typical household stoves. PICs include: small respirable particles, gases such as carbon monoxide and nitrogen, phenols, quinones/semiquinones, chlorinated acids such as methylene chloride, and dioxins. Combustion of coal may release, in addition to the above pollutants, sulfur oxides, heavy metal contaminants, arsenic, and fluorine. On average, a typical solid fuel stove converts 6–20% of the fuel into toxic substances. At least 28 pollutants present in smoke from solid fuel use have been shown to be toxic in animal studies; some 14 carcinogenic compounds and four cancer-promoting agents have been identified (Table 4.2).

In a recently concluded assessment by the International Agency for Research on Cancer, emissions from household combustion of coal have been classified as being "carcinogenic to humans" (Group 1 carcinogen, based on sufficient human and experimental evidence), while indoor emissions from household combustion of biomass fuel (mainly wood) has been classified as "probably carcinogenic to humans" (Group 2A carcinogen, on the basis of limited evidence of carcinogenicity of biomass combustion emissions, mainly from wood, in humans and experimental animals; sufficient evidence of carcinogenicity of wood-smoke extracts in experimental animals; and strong evidence of mutagenicity) (IARC, 2010).

4.2.5 Exposures to Health-Damaging Pollutants from Combustion of Household Fuels

Well over 100 studies over the last two decades have assessed levels of indoor air pollutants in households using solid fuels. The methods employed range from the collection of questionnaire-based information to quantitative measurements of household-level exposures. A global database documenting results from these measurements across some 70 studies in the developing countries of Asia, Latin America, Africa, and China (if reported in English) is available from WHO (2005). Although a great majority of studies have performed single-pollutant measurements on a cross-sectional sample of households, select studies have examined temporal, spatial, or multi-pollutant patterns, in addition to day-to-day or seasonal variability in concentrations and exposures (Saksena et al., 1992; Ezzati et al., 2000; Balakrishnan et al., 2002; He et al., 2005). A few have also developed models to examine the differential contributions of household determinants and validate the use of simpler household indicators (that are relatively easy to collect) as a proxy for actual household exposures (Balakrishnan et al., 2004; Bruce et al., 2004).

Data from more than 70 studies are available in the global indoor air pollution databases (Saksena et al., 2003), with some 30 new studies added in a recent update. Nearly one-third of the studies are from South Asia; Latin America, Africa, East Asia, and Eastern Mediterranean are also well represented. On a country-by-country basis, India reported the most studies (27), followed by China (13), Guatemala (10), and Mexico (10). Other countries generally reported fewer than five studies. While most studies reported results from rural areas, 34 studies reported on urban households, indicating a substantial use of solid fuels in urban settings of developing countries. These measurements cover approximately 13,000 households worldwide.

Wood was the most commonly reported solid fuel, with many studies reporting wood, wood chips, and agricultural residues in aggregate or as "mixed fuels." Similarly, gaseous and liquid fuels were often reported as "mixed clean fuels" rather than individually. Prior to 2000, most studies reported measurements from households using traditional solid fuel stoves, while more recently nearly 30 studies have reported results from households using self-styled "improved (solid fuel) stoves."

Table 4.2 | Toxic pollutants from incomplete biomass combustion.

Pollutant	**Known Toxicological Characteristics**
Particulates (PM_{10}, $PM_{2.5}$)	Bronchial irritation, inflammation increased reactivity, reduced mucociliary clearance, reduced macrophage response
Carbon monoxide	Reduced oxygen delivery to tissues due to formation of carboxyhemoglobin
Nitrogen dioxide (relatively small amounts from low temperature combustion)	Bronchial reactivity, increased susceptibility to bacterial and viral lung infections
Sulfur dioxide (relatively small amount from most biomass)	Bronchial reactivity (other toxic end points common to particulate fractions)
Organic air pollutants	
Formaldehyde 1,3 butadiene Benzene Acetaldehyde Phenols Pyrene, Benzopyrene Benzo(a)pyrene Dibenzopyrenes Dibenzocarbazoles Cresols	Carcinogenicity Co-carcinogenicity Mucus coagulation, cilia toxicity Increased allergic sensitization Increased airway reactivity

Source: Naeher et al., 2007.

Table 4.3 | Distribution of particulate matter concentrations in households using solid fuels in traditional stoves.

Type of fuel	Number of households	Mean (µg/m³)	Median (µg/m³)	Standard Deviation
Wood	3269	2097	858	3893
Dung	159	7756	2619	11200
Charcoal	231	3926	1190	8396
Coal	134	820	533	579
Mixed solid fuel	3506	591	575	456
Fuel unspecified	341	537	298	566
Kerosene	283	270	100	422
LPG/ Methane /Electricity	5821	316	139	371
Mixed Liquid/ Gaseous fuel	76	376	398	149

Notes: Data include all size fractions and sampling durations.

Source: author's calculations based on data from 108 studies in the revised WHO Global Indoor Air Pollution Database (WHO, 2005).

Particulate matter of various sizes was the most commonly measured pollutant, followed by carbon monoxide. Other air toxics were seldom reported. While earlier studies measured total suspended particulate matter (TSP) over short sampling times (e.g., during cooking), many recent studies report results of PM_{10} or $PM_{2.5}$ over 24-hour periods. Table 4.3 shows the distribution of measured values across studies that used alternative fuels.[3]

3 It should be noted that PM_{10} and $PM_{2.5}$ are generic particle classes defined simply by the upper limit of the particle diameters contained within that class (i.e., 10 or 2.5 micrometers). These metrics encompass particles of any chemical composition whose aerodynamic diameters fall below the respective size, potentially including sulfates, nitrates, metals, elemental and organic carbons.

Median values in households using liquid or gaseous fuel are observed to be 5- to 10-fold lower than those reported for households using solid fuel. When compared with more carefully done studies, however, the levels in households using gaseous fuel is often 10- to 20-fold lower. Peak values in dung- and coal-using households have occasionally been observed to be 100-fold higher than levels in corresponding gas-using households.

Households using solid fuels experience indoor concentrations many times higher than WHO Air Quality Guidelines (AQG) for PM_{10} and $PM_{2.5}$ (WHO, 2006). Even gas-using households in rural areas barely meet the strictest AQG values, presumably due to a high background

Table 4.4 | Mortality and morbidity attributable to indoor air pollution from solid fuel use, by global region, 2004.

	Attributable deaths per year		Attributable DALYs per year	
	Number ('000)	Per 1 million population	Number (in millions)	Per 1 million population
Developing countries	1,994	378	40.5	7,878
LDCs	577	771	18.4	24,606
Sub-Saharan Africa	551	781	18	25,590
South Asia	662	423	14.2	9,075
Arab States	35	114	1.1	3,489
East Asia and Pacific	665	341	6.5	3,308
Latin America and Caribbean	29	54	0.7	1,334
World	1,961	305	41	6,374

Notes: Numbers and rates of deaths and disability-adjusted life years (DALYs) for all causes – i.e., child pneumonia, adult COPD, and adult lung cancer.

Source: UNDP, 2009.

of outdoor air pollution resulting from the venting and dispersion of solid fuel smoke from neighboring households.[4]

Collectively, the evidence from these studies shows that rural women, children, and men in households using solid fuels experience extremely high levels of exposure to particulate matter and toxic gases. Often these exposures are an order of magnitude or even higher than levels generally considered safe. Further, some emissions from coal combustion (e.g., arsenic and fluorine) have additional, non-inhalational exposure routes (such as deposition on food and contamination of drinking water sources), compounding health effects (He et al., 2005).

4.2.6 Health Effects Associated with Household Fuel Combustion

The amount of disease resulting from the use of solid fuels has been estimated (Smith et al., 2004) as part of WHO's CRA (WHO, 2002; Ezzati et al., 2004). The burden of disease is calculated by combining information on the increased risk of a disease resulting from exposure with information on how widespread the exposure is in the population (in this case, the percentage of people using solid fuels). This allows for the calculation of the "population attributable fraction" (PAF), which is the fraction of the disease seen in a given population that can be attributed to a particular exposure – in this case, solid fuel use. Applying this fraction to the total burden of disease (e.g., child pneumonia expressed as deaths or DALYs), gives the total number of deaths and DALYs that result from use of solid fuels.

For computing disease burdens associated with solid fuel use, estimates of relative risk obtained from all published epidemiological studies have been combined together in a process called meta-analysis into a single best estimate of the risk. In the 2004 CRA, three diseases were felt to have sufficient evidence bases to be included in the final estimate of the health burden of solid fuel use: pneumonia in children aged under five years, chronic obstructive pulmonary disease (COPD), and lung cancer (only for use of coal). The 2004 WHO-led CRA exercise estimated that annually about 1.6 million deaths and over 38.5 million lost healthy life years (also measured in DALYs) were attributable from household solid fuel use in 2000 (Table 4.4) (Smith et al., 2004).[5] Cooking with solid fuels is thus responsible for a significant proportion, about 3%, of the global burden of disease. In many poor countries, such as India, solid fuel use was found to be the third most important risk factor for ill health, exceeded only by malnutrition and unsafe water and sanitation (Smith and Ezzati, 2005).

The regional or national burden of disease attributable to solid fuel use varies considerably and is based not only on differences in fuel use but also on underlying disease rates. For example, among developing countries, attributable deaths from COPD are greater in India and China as compared to least developed countries (LDCs) and sub-Saharan Africa, while attributable deaths from child pneumonia are highest in the latter because of different patterns of background disease rates. It is to be emphasized that child pneumonia accounts for some 75% of DALYs attributable to solid fuel use in developing countries overall (compared with less than half of all premature deaths) and an even greater share of DALYs in the LDCs and sub-Saharan Africa. In India, for example, pneumonia accounts for more than half of all DALYs attributable to solid fuel use, but only about a third of premature deaths. Because the DALY measure captures the many years of life lost due to deaths from child pneumonia, it shows an even stronger impact of solid fuel use on health in the poorest countries, where pneumonia is a major cause of death in children under five years of age. As expected, the poorest are at the greatest risk of exposures and disease burdens wherever they are found.

At the time of the preparation of the CRA (~2002), the evidence for attributable disease burden was sufficient only for the three health outcomes

4 The completed global indoor air pollution measurement database is expected to be available on the WHO website in 2012: www.who.int/indoorair/health_impacts/databases_iap/en/

5 As noted in Footnote 1, a completely revised update will be available on the WHO website in 2012.

mentioned above (i.e., child pneumonia, COPD, and lung cancer). An emerging body of evidence, however, indicates additional burdens from other diseases and conditions, including new studies on cataracts, low birth-weight, and tuberculosis, as well as lung cancer associated with biomass fuel use (Lin et al., 2007; Pope et al., 2010; Hosgood III et al., 2011). Although not yet conclusive, there is also growing evidence of other cancers and burns related to biomass fuel use. Evidence on the original health outcomes is growing as well; see Dherani et al. (2008) for information on pneumonia, Kurmi et al. (2010) on COPD, and the IARC (2010) on lung cancer from coal. In addition, results will soon be available from the first randomized controlled trial for an intervention related to solid fuel use, through the use of chimney stoves in Guatemala (Smith et al., forthcoming). Although there have not been any studies of heart disease in these settings, substantial evidence from other exposures to combustion particles (outdoor air pollution, environmental tobacco smoke, and active smoking) together provide strong, although indirect, evidence of a probable major impact from household fuels as well (Pope et al., 2009; Smith and Peel, 2010).[6]

For the future scenarios used in GEA, a simplified health assessment was conducted using the same relative risks published in the 2004 CRA, as well as new relative risks for ischemic heart disease published in Wilkinson et al. (2009),but with changing exposures as advanced stoves and fuels come into use in the next decades (in line with GEA assumptions). GEA estimated premature mortality from household fuels in 2005 using this approach was 2.2 million, which is somewhat higher than what was found for 2000 in the CRA. The methods used are discussed in detail in Chapter 17.[7]

4.2.7 Intervention Effectiveness

Household energy interventions to date have largely centered on improving fuel efficiency, either by using better fuels and stoves or using improved stoves with the same fuels (Barnes et al., 1994). Considerable evidence is available to indicate that households using gaseous (liquified petroleum gas or biogas) or liquid fuels experience considerably lower pollution levels as compared to homes using solid fuels (Albalak et al., 2001; Balakrishnan et al., 2002; Balakrishnan et al., 2004). A limited number of studies have also shown significant reductions with the use of electricity (Rollin et al., 2004). Improved biomass stoves, which burn more efficiently and vent emissions outside the home, have been an intervention option for more than two decades. Improved stove programs have been implemented in many countries, most notably in India and China. Although designed to conserve fuel, these programs have had some impacts on reducing household emissions of health-damaging pollutants and CAPs (US EPA, 2000; Edwards et al., 2004).

Somewhat lower indoor concentrations using stove models equipped with chimneys have also been documented in many regions, including China (Sinton et al., 2004), India (Smith et al., 1983; Ramakrishna et al., 1989), Nepal (Reid et al., 1986; Pandey et al., 1990), Latin America (Brauer and Bartlett, 1996; Albalak et al., 2001; Bruce et al., 2004), Mexico (Riojas-Rodríguz et al., 2001), and sub-Saharan Africa (UNDP, 2009). Interventions that reduce exposures either through behavioral interventions or through improved ventilation have also been described (Barnes et al., 2004; UNDP, 2009).

More recently, advanced combustion stoves – using traditional woodfuel but burning much more cleanly – have become available. One promising approach involves so-called "gasifier" stoves that achieve very high combustion efficiency through designs that facilitate two-stage combustion. The most reliable of these use small electric blowers to stabilize the combustion. Where there is no reliable electricity available, inexpensive thermal-electric generators (TEGs) are now being incorporated into stoves to generate the needed power from the stove heat itself.

Although programs promoting the use of improved stoves have not always proved successful, some have achieved remarkable penetration. For example, the Chinese National Improved Stove Programme was able to provide stoves to some 180 million rural households during the 1980s and 1990s (Barnes et al., 1993; Smith et al., 1993; Sinton et al., 2004). Several programs are underway in India that attempt to promote penetration of improved stoves using market-based approaches, in contrast with earlier, government-subsidized efforts. While substantial reductions in emissions have been achieved with many of these improved stove models, the residual levels of pollutants are still high compared to WHO's health-based AQGs. More recent programs increasingly emphasize not only the provision of stoves, but also support for installation and routine maintenance, training and education, and use of market mechanisms to continuously assess user preferences. These innovations are expected to expand coverage and improve performance, leading to further sustained exposure reductions across large populations.

Some evidence suggests that health benefits can accrue even with modest reductions in exposures. In the trial with chimney stoves in Guatemala, a 50% reduction in smoke exposures resulted in an 18% reduction in physician-diagnosed childhood pneumonia (Bruce et al., 2007; Smith et al., forthcoming). To achieve this, however, required nearly a 90% reduction in indoor levels, which is difficult to achieve reliably in practice without advanced combustion stoves. In those households achieving a 90% reduction in exposure, on the other hand, children had only half as much pneumonia, an improvement greater than achieved by available vaccines and nutrition supplements, which are the other major interventions for this major killer of children. To obtain this much reduction, however, will require extremely clean burning stoves used regularly over long periods.

6 See Footnote 2.

7 As noted in Footnote 1, readers interested in the burden of disease attributable to household air pollution or outdoor air pollution in 2005 or 2010 are advised to refer to the updated CRA on the WHO website, as it is part of a larger consensus assessment in which fair comparisons were made across risk factors. Please note that the CRA does not attempt to project changes in burden of disease over future years as does GEA in Chapter 17.

Table 4.5 | Health benefits of the Indian Improved Stove Program, 2010–2020 (estimated).

	Deaths from ALRI	Deaths from COPD	Deaths from IHD	Total DALYs for these diseases
Avoided in 2020 (%)	30.2	28.2	5.8	17.4
Annual number in 2020 without stoves (x10^6)	0.14	1.00	1.77	63.0
Total avoided 2010–20 (x10^6)	0.24	1.27	0.56	55.5

Note: ALRI = acute lower respiratory infections. COPD = chronic obstructive pulmonary disease. IHD = ischaemic heart disease. DALY = disability-adjusted life year.

Source: Wilkinson et al., 2009.

In a striking set of analyses, simulations to estimate percent use of improved stoves under baseline and assumed enhanced rates of dissemination for the case of India have shown that nearly 12,500 DALYs could be avoided annually per million people. The national burden of disease (DALYs) in 2020 from these three major diseases is estimated to be about a sixth lower than it would have been without the stove program, which is equivalent to the elimination of nearly half the entire cancer burden in India in 2020 (Table 4.5 and Wilkinson et al., 2009). What is not well understood yet, however, is how well such advanced stoves actually perform in field conditions and how well they are accepted by large populations.[8]

4.2.8 Conclusion

The UNDP report of 2009 assesses that while many developing countries have clear targets for providing access to electricity, only a handful (17 for access to modern cooking fuels and 11 for provision of improved stoves) have set targets to reduce household solid fuel use. Evidence of health benefits from incremental improvements could be expected to provide relevant cost-effectiveness information to policy makers, greatly facilitating the acceleration of intervention efforts. To effectively implement stoves that truly lower exposures, however, there is a need to define more quantitatively what is meant by various levels of "improvement," probably separately in terms of expected emissions/exposure and fuel use per meal. In the past, unfortunately, almost any new stove could be claimed to be "improved" when many actually did little. Fortunately, the WHO has embarked on the process to develop formal health-based guidelines, slated for publication in 2012.[9] Another factor stove programs need to address directly is adoption/usage – it does no good to disseminate a high-performance stove that no one uses, something that has happened in many past programs. New monitoring technologies, however, are making it possible to keep track of actual household usage inexpensively (Ruiz-Mercado et al., 2011). This will allow programs to better understand the stove designs, training, and incentives that enhance usage.

8 In 2010, a number of non-governmental organizations; foundations; international, bilateral, and national agencies and companies announced the formation of Global Alliance for Clean Cookstoves. Its goal is to engender the introduction of 100 million clean-burning cookstoves globally by 2020. See http://cleancookstoves.org/the-alliance/.

9 For more information, see www.who.int/topics/air_pollution/en/.

4.3 Occupational Health Effects of Energy Systems

4.3.1 Key Messages

- Energy systems involve a large number of workers, particularly in low- and middle-income countries, and entail significant occupational health problems.
- Solid fuel systems (i.e., biomass and coal) tend to have higher occupational risks, in both absolute and per-worker terms.
- Despite substantial gains over the past 50 years at some energy-related workplaces, health and safety systems do not exhibit best practices in many countries. Health risks could be reduced with the adoption of modern occupational health management and prevention programs, in accordance with international conventions and guidance from the International Labour Organization (ILO).
- Renewable energy systems, such as hydropower, wind power, and photovoltaic power, likely involve lower occupational health risks. These risks occur mainly during construction work.
- Occupational health hazards for each type of energy source need to be assessed at the local level, followed by the creation of a plan for effective health protection. Such assessments should also include analysis of occupational health co-benefits of changing to more renewable energy sources.

4.3.2 Background

Energy production, processing, transport, waste disposal, and end use involves millions of workers around the world. In addition, the construction work required to build the energy supply units requires large numbers of additional workers. The health hazards they are exposed to during work activities are important concerns for the energy industry. Many of these jobs are hazardous, with particular risks of injuries, dust diseases, poisoning, noise/induced hearing loss, heat stroke, and radiation effects.

Energy-related work for rural and urban people living in poverty primarily involves the collection of biomass fuel for daily household cooking and heating needs. Their work involves injury risks, heavy load bearing and heat exposure in bright sun during the hot season, the latter being exacerbated by global climate change. In some areas, risks of physical violence, snake bite, and leeches accompany biomass collection for women. Biomass fuel collection may also occur in dumps and landfill sites, which increases the risks of injuries and chemical exposures for the collectors. Much of the work needed for household energy supply in the developing countries is carried out as a household task that does not figure in the national statistics as an "occupational" issue.

Coal as an energy source involves coal mining, one of the most hazardous occupations on Earth. Miners are exposed to collapsing mine shafts, fire and explosion risks, toxic gases (carbon monoxide), lung-damaging dusts (coal and silica), and hot work environments, as well as injury and ergonomics hazards. Coal also requires major transport arrangements for coal and waste that create health hazards. Oil and gas workers face injury risks, particularly during drilling and emergency situations and work on offshore platforms, as well as exposure to toxic materials at refineries. The Gulf of Mexico oil platform disaster in 2010 is an example of the extreme hazards involved.

Hydropower electricity production on a large scale requires major dam, tunnel, and building construction, which also entails high injury risks and exposure to noise and heat. Mini- and micro-hydro schemes do not require such major infrastructure.

Wind power, photovoltaic solar power, and solar water heating involve more limited occupational hazards during construction and are associated with risks of manufacturing steel, cement, and other materials, while nuclear power has its own special hazards associated with potential radiation exposure and the disposal of radioactive waste (see Sections 4.7 and 4.8).

This section will analyze the health issues based on the type of energy source and give examples of how the effects have been documented in different countries. The ILO Encyclopedia of Occupational Safety and Health (ILO, 1998) was published more than 10 years ago but is still a very useful source of information on occupational health aspects of energy systems. This section therefore refers to "older" sources from that period, but that does not mean that the health information is out of date. Ideally, there would be data on the occupational health impacts of different energy sources expressed as "burden of disease and injury per megawatt-hour of energy supply," but these are not yet available.

The analysis of occupational health impacts of different energy systems should include a full life-cycle analysis of the extraction, transport, and processing of raw materials; the production of machinery and buildings required; and the transportation and disposal of waste from the process, as well as the actual energy medium (see Box 4.4 (p 205)).

4.3.3 Biomass

Wood, agricultural plant waste, cow dung, etc., are common sources of cooking and heating energy in poor households in developing countries. Wood is still also widely used in developed countries for space heating, in some cases promoted in the interest of reducing CAP emissions (UNDP, 2000). Biomass constitutes approximately 9% of the global primary energy supply. A detailed review of the occupational health and safety issues of forestry can be found in Poschen (1998a). Additional and updated information can be searched, for instance, on the website "Atlantic Network for Research in Forestry Occupational Health, Safety and Ergonomics."[10]

The majority of wood and agricultural waste, etc. is collected by women and children in local fields and forests (Sims, 1994). This is a part of the daily survival activities, which also include water hauling, food processing, and cooking. An analysis of time use for these activities in four developing countries (Reddy et al., 1997) showed that women spent 9–12 hours per week doing this, whereas men spent 5–8 hours. Women's role in firewood collection was most prominent in Nepal (2.4 hours for women and 0.8 hours for men). Updated similar information about sub-Saharan Africa is now available (Blackden and Wodon, 2006). Firewood collection may be combined with harvesting of wood for local use in construction and small-scale cottage industry manufacturing. This is subsistence work, often seasonal, unpaid, and unrecorded in national economic accounts. Globally, about 16 million people were involved in forestry in the 1990s (Poschen, 1998b), more than 14 million of them in developing countries and 12.8 million of them in subsistence forestry (UNDP, 2000).

A number of health hazards are associated with the basic conditions of the forest. The workers have a high risk of suffering from insect and snake bites, stings from poisonous plants, cuts, falls, and drowning. In tropical countries, the heat and humidity create great strain on the body (Wasterlund, 1998; Kjellstrom et al., 2009), whereas in temperate countries the effect of cold climate is a potential hazard. The work is outside, and, in low-latitude countries, high levels of ultraviolet radiation can be another health hazard, as it increases the risk of skin cancer and cataracts (WHO, 1994). All forestry work is hard physical labor, often causing repetitive stress injuries, such as painful backs and joints, as well as fatigue, which in turn increases the risk of injuries from falls, falling trees, or equipment (Poschen, 1998b). Women and children carrying very heavy loads of firewood are a common sight in areas with subsistence forestry (Sims, 1994). Children may also drop out of school due to the need to help with family forestry work. In addition, the living conditions of forestry workers are often poor quality, and workers may be spending long periods in simple huts in the forest with limited protection against the weather and poor sanitary facilities (UNDP, 2000).

Urbanization leads to the development of a commercial market for firewood and larger-scale production of firewood from logs or from smaller waste material left over after the logs have been harvested. Energy forestry then becomes more mechanized and the workers are exposed to additional

10 www.safetynet.mun.ca/forestry/index.htm

hazards associated with commercial forestry (Poschen, 1998b). Motorized hand tools (e.g., the chain saw) become more commonly used, which leads to high injury risk, as well as noise-induced hearing loss and "white finger disease" caused by vibration of the hands. In addition, synthetic fertilizer and pesticides become a part of the production system, with the potential for pesticide poisoning of workers (UNDP, 2000).

As the development of forestry progresses, more and more of the logging becomes mechanized with very large machinery involved, which reduces the direct contact between worker and materials. Workers in highly mechanized forestry have only 15% of the injury risk of highly skilled forestry workers using chainsaws (Poschen, 1998b). However, firewood production remains a hazardous operation because it requires manual handling of the product close to cutting tools (UNDP, 2000).

Another health aspect of wood-based energy is the risk of burning wood that has been treated against insect damage with copper-arsenic compounds or painted with lead paint. Such wood may be more difficult to sell, and may therefore be used to a greater extent by the firewood production workers themselves in stoves and open fires. When burnt, poisonous arsenic and lead compounds, as well as dioxins and furans, are emitted with the smoke and can lead to ill-health when inhaled (UNDP, 2000; Tame et al., 2007).

4.3.4 Coal

Coal is a major energy source, constituting approximately 25% of total primary energy (see Chapter 1). Coal can be produced through surface mining ("open cast") or underground mining. Both operations are inherently dangerous to workers. About 1% of the global workforce is engaged in mining, but they account for 8% of the global fatal occupational accidents (about 15,000 per year) (Jennings, 1998). Since 1900, over 100,000 people have been killed in coal mining accidents in the United States, and in China, underground mining accidents cause 3,800–6,000 deaths annually (Epstein et al., 2011). A detailed review of occupational health and safety issues in coal mining and other mining is available in Armstrong and Menon (1998).

Underground coal miners are exposed to the hazards of excavating and transporting materials underground. This includes injuries from falling rocks and falls into mine shafts, as well as injuries from machinery used in the mine. There are no reliable global data on injuries of this type from developing countries (Jennings, 1998), but in developed countries miners have some of the highest rates of compensation for injuries. The situation is likely to be worse in developing countries. In addition, much of the excavation involves drilling into silica-based rock, which creates high levels of silica dust inside the mine. Occupational lung disease (silicosis) is therefore a common health effect in coal miners (Jennings, 1998). In addition, coal miners have an increased risk of lung cancer (Donoghue, 2004).

Other health hazards specific for underground coal mining include the coal dust, which can cause "coal workers' pneumoconiosis" or anthracosis (black lung disease), often combined with silicosis (Ross and Murray, 2004). Since 1900, coal workers' pneumoconiosis has killed over 200,000 people in the United States; in the 1990s alone, over 10,000 former US miners died from the disease. The prevalence has more than doubled since 1995 (Epstein et al., 2011).

The coal dust is explosive, and explosions in underground coal mines are an ever-present danger for coal miners. Coal is also inherently a material that burns, and fires in coal mines are not uncommon. Once such a fire has started it may be almost impossible to extinguish it. Apart from the danger of burns, the production of smoke and toxic fumes will create great health risks for the miners. Even without fires, the coal material will produce toxic gases, such as carbon monoxide, carbon dioxide, and methane, when it is disturbed (Weeks, 1998). Carbon monoxide is extremely toxic, as it binds to hemoglobin in the blood, blocks oxygen transport, and causes "chemical suffocation" (WHO, 2000). It is a colorless and odorless gas, giving no warning before symptoms such as drowsiness, dizziness, headache, and unconsciousness occur. Carbon dioxide can sometimes displace oxygen in the underground air and can cause suffocation. Another health hazard in mining is exhaust fumes from diesel engines used in machinery or transport vehicles underground. These exhausts contain very fine particles, nitrogen oxides, and carbon monoxide, all of which can create serious health hazards (WHO, 2000).

Work in coal mines is also uncomfortably hot during the warmer seasons of the year (Kampmann and Piekarski, 2005). In both Germany and South Africa, heat impacts on mine workers increase during and just after the summer season. Ongoing climate change is expected to increase the occupational health risks related to coal mining.

Surface coal mining avoids the hazards of working underground but does still involve injury risk from machinery, falls, and falling rocks. In addition, coal mining is very physically intensive work, and heat, humidity, and other weather factors can affect workers' health (Kjellstrom, 2009). The machinery used is noisy and hearing loss is a common effect in miners (Armstrong and Menon, 1998). Another health hazard is the often squalid conditions under which many coal workers in developing countries live, creating particular risk for the diseases of poverty (Jennings, 1998). In addition, many modern coal mines involve mountaintop removal and strip mining, which adds to ecological damage, causes mental stress among nearby communities, leads to ammonia releases, and contaminates water sources with waste emissions (Epstein et al., 2011).

After extraction the coal needs to be processed and transported to the sites where it will be used, including residential areas, power stations, and factories. This creates other types of occupational hazards (Armstrong and Menon, 1998). For instance, coal for residential use is often ground and formed into briquettes. This work involves high levels of coal dust, as well as noise hazards. Loading, transportation, and offloading of large amounts of coal involves ergonomic hazards, noise, and injury hazards (UNDP, 2000).

The use of coal on a large scale in power stations or industry creates yet more hazards. One of the more specific hazards is the conversion of coal to coke in steel production. This process, though not entirely associated with energy supply, distills off a large number of volatile polycyclic aromatic hydrocarbons in coal, the so-called "coal tar pitch volatiles" (Moffit, 1998). Coke oven workers have twice the lung cancer risk of the general population (IARC, 1984). Additional health hazards for workers are created when the large amounts of ash produced in power stations or by industry need to be transported and deposited. The health hazards of power generation workers have been reviewed by Crane (1998).

4.3.5 Oil and Gas

Oil and gas exploration, drilling, extraction, processing, and transportation involve a number of hazards, including heavy physical labor, ergonomic hazards, injury risk, noise, vibration, and chemical exposures (Kraus, 1998). This type of work is often carried out in isolated geographic areas with inclement weather conditions. Long-distance commuting may cause fatigue, stress, and traffic accident risks (UNDP, 2000).

The ergonomic hazards lead to risk of back pain and joint pain. Injuries include burns and those caused by explosions. Skin damage from exposure to the oil itself and from chemicals used in the drilling processes creates a need for well-designed protective clothing (Kraus, 1998). In addition, many oil and gas installations have used asbestos in insulating cladding on pipes and equipment. This creates the hazard of inhaling asbestos dust during the installation and repair of such equipment. This in turn creates a risk of lung cancer, asbestosis and mesothelioma (WHO, 1998).

Much exploration and drilling for oil and gas now occurs offshore. The Gulf of Mexico catastrophe in 2010 highlighted the hazards involved, including underwater diving work, which is inherently dangerous. In addition, the weather-related exposures can be extreme, particularly as the work often requires continuous, around-the-clock operations (Kraus, 1998). Transport to and from the oil rig is another hazard (Gardner, 2003).The work is also stressful due to its shift-work character, characterized by long work shifts and extended periods in cramped, crowded living conditions (Knutsson, 2003).

4.3.6 Hydropower

This type of energy generation has its own set of occupational health hazards (McManus, 1998). Constructing a hydroelectric power station usually means building a large dam, excavating underground water channels, and erecting large structures to house the electricity generator. McManus (1998) lists 28 different hazards involved in the construction and operation of these power stations, including chemical exposures from paints, oils, and polycholrinated biphenyls (PCBs); asbestos exposure; diesel fumes; welding fumes; work in confined spaces or awkward positions; drowning; electrocution; noise; heat; electromagnetic fields; and vibration (UNDP, 2000).

Much of the construction of new hydropower stations occurs in low- and middle-income countries (see International Energy Agency databases), where occupational health management and prevention may be laxer than in high-income countries. Thus, expanded use of hydropower, as an element of policies to reduce GHG emissions, must entail the application of up-to-date occupational health standards.

4.3.7 Nuclear

Nuclear power generation has its own particular hazards due to the radiation hazards involved in mining, processing, and transporting uranium, as well as the radiation present in the power station itself. These hazards are addressed in Section 4.7 below.

4.3.8 Other Electricity (Wind, Solar, Waste)

The manufacture of equipment used in the wind power and solar power industries involves the hazards typical of manufacturing industries, including injuries, noise, and chemical exposures. In addition, the technologies for solar electricity generation involve new chemical compounds, some based on rare metals, with poorly understood toxic properties. These risks are discussed in Section 4.8 below.

4.3.9 Number of Workers and Quantitative Health Effects Comparisons

Much of the comparative analysis of the human impacts of various energy systems has been carried out as economic analysis (e.g., Pearce, 2001). Energy policy analysis often assesses "externalities" of different types, but occupational health issues are not always included and the "life-cycle" approach mentioned earlier (Sorensen, 2003) is not always applied. A comparison of wind and coal as energy sources in the United States (Jacobson and Masters, 2001) concluded that wind was at a great advantage, with one key rationale being the high occupational mortality in coal mining. Another more comprehensive analysis (Rabl and Dreicer, 2002) highlighted the lower health and economic impacts of renewable energy systems compared to coal.

Comparisons of the occupational health aspects of energy systems require data on the number of workers involved, as well as the level of occupational health risks in each system and the different elements of the lifecycle of that system. The number of people necessary for each type of energy system to meet the energy requirements of a community is difficult to estimate accurately. As mentioned earlier, much of the work done to supply the energy needs within the poorest communities is carried out by family members, particularly women, who are not employed in the formal sense. In addition, much of this work is carried out by small enterprises, and is not always recorded in national employment statistics.

In the ILO Encyclopedia on Occupational Health (Hamilton, 1998) a summary table outlines the occupational health and general public health impacts of selected energy systems used in electricity generation (Table 4.6). Each of these systems has important occupational health effects; it is unfortunate that a comparison with renewable energy sources was not included.

Mining is a particularly dangerous occupation and miners are a large occupational group in the international statistics (e.g., the UN Demographic Yearbooks and the Laborsta database at the International Labor Organization). They represent up to 2% of the economically active population in certain developing countries (Kjellstrom, 1994), but the breakdown by different types of mining work is not always reported. Coal mining is, however, a common type of mining in certain developing countries.

Table 4.7 highlights the high occupational mortality rates in mining in the official statistics of a number of countries. It is likely that in some developing countries a number of occupational deaths are excluded from these statistics due to the limited scope of reporting and assembling statistical information. The table also shows that workers in the electricity (and other infrastructure occupations) have a higher mortality rate than the country averages.

It should be emphasized that these risk estimates are based on the current situation and the risks in many countries and for several energy systems can be significantly reduced if appropriate occupational health

Table 4.6 | Significant health effects of technologies for generating electricity.

Technology	Occupational Health	Public Health
Biomass	Trauma from accidents during gathering and processing Exposure to hazardous chemical and biological agents	Air pollution health effects Diseases from exposure to pathogens Trauma from house fires
Coal	Black lung disease Trauma from mining accidents Trauma from transport accidents	Air pollution health effects Trauma form transport accidents
Oil	Trauma from drilling accidents Cancer from to refinery organics	Air pollution health effects Trauma from explosions and fires
Oil shale	Brown lung disease Cancer from exposure to retorting emissions Trauma from mining accidents	Cancer from exposure to retorting emissions Air pollution health effects
Natural gas	Trauma from drilling accidents Cancer from exposure to refinery emissions	Air pollution health effects Trauma from explosions and fires
Tar sands	Trauma from mining accidents	Air pollution health effects Trauma from explosions and fires

Source: Hamilton, 1998.

Table 4.7 | Fatal occupational injury rates per 100,000 workers; crude rates for all occupations and rate ratio between mining and all occupations.

Country	Crude Occupational Mortality Rate, all occupations (per 100,000 workers)	Rate Ratio, mining workers vs. all occupations
Argentina	15	3
Nicaragua	10	6
El Salvador	10	4.5
South Korea	12	12
Hong Kong	7.5	11
Zimbabwe	7	3.5
Japan	2	8
Sweden	1.5	6
United Kingdom	0.7	13

Notes: Based on rates per 100,000 insured workers or rates per million work hours and 2000 hours per worker and year. Recent years, 2006 or average of five recent years until 2006, approximate figures, men and women combined. These data most likely underestimate the true rates and should be seen as indicative, of the additional risks in mining. The rates for electricity workers are in a number of countries similar to the rates for mining. Most countries provide incomplete information to ILOs website.

Source: ILO website, Laborsta, 2009.

standards are applied. The differences in mining mortality risks in Table 4.7 between countries such as Sweden or Japan and the other countries, even developed countries, are likely to indicate the impacts of good preventive occupational health programs.

4.3.10 Conclusion

Biomass and fossil fuel systems have a number of occupational health problems and involve very large numbers of workers, particularly in low- and middle-income countries. Major successful efforts to reduce occupational risks in the energy supply chain can be demonstrated during the last 50 years, but in many mines, construction sites, and power stations, the health and safety systems are not commensurate with best practice. The health risks can be further reduced if modern occupational health management and prevention programs are applied in all countries and all energy supply sites. International conventions and guidelines from the ILO can be used as a basis for such applications.

Renewable energy systems such as hydropower, wind power, and photovoltaic solar power most likely involve less occupational health risks, while nuclear power has special hazards with low probability but enormous health impact if a major accident occurs. Further comparative analysis of the occupational health risks in different energy systems would be of great value.

Each energy investment project should include a detailed occupational health and safety impact assessment as well as a strategy and program to implement prevention. This program should identify the initial and ongoing costs for maintenance of the program, and these should be included in future budgeting.

4.4 Community Effects of Energy Systems

4.4.1 Key Messages

- Air pollution emissions from fuel combustion is a major risk factor for morbidity and mortality in communities, particularly for people living in poverty, who often rely on low-quality energy sources and technologies. Within and across communities, vulnerability to pollution-related health risks varies as a function of age and income.

- Community air quality is relatively good and improving in most developed countries, and relatively poor and deteriorating in many developing countries.

- Exposure to outdoor particle air pollution, largely due to fuel combustion, is estimated by GEA to have been responsible for about 2.7 million premature deaths in 2005.[11]

- In developed-world communities, transportation emissions are a particularly important cause of health burdens, due both to the nature of the emitted pollutants and the close proximity of emissions to vulnerable populations. Energy use in buildings also makes a significant contribution.

- In developing-world communities, the situation is more complex, with contributions from vehicles, industry, trash burning, household biomass fuels, agricultural burning, and other sources. Health burdens associated with community energy use are largest in developing-world cities, especially in China and India.

- Experiences from developed countries indicate that outdoor pollution levels can be greatly reduced through the application of control technologies on combustion and shifts to non-combustion sources of energy.

4.4.2 Background

Communities are residential groupings of people ranging in size from small rural villages to large, densely populated megacities. Patterns of energy use and resulting health impacts vary with size, and also with economic development. Within communities, vulnerability to pollution exposures and health impacts varies considerably across the population, with the young, old and those living in poverty often at greatest risk. Community-scale use of energy and associated environmental health consequences will increase in importance as populations continue to concentrate in urban areas, particularly in developing countries.

For the purposes of this section, the wide spectrum of communities measured on scales of density and economic development has been simplified to three representative categories: large developing-world cities, large developed-world cities, and low-density, peri-urban communities in the developed world. This simplification helps to organize the discussions that follow. However, it should be recognized that tremendous heterogeneity exists within these categories. Where particularly relevant, variations within categories are highlighted. (We exclude the category of rural villages in developing countries because energy use in this setting is usually dominated by solid fuel combustion for cooking, an issue dealt with in Section 4.2.)

Energy-related health impacts can arise in community settings either when fuel storage, processing, or combustion occurs within the community itself (e.g., due to exposures to fuel or combustion products), or when it occurs someplace else (e.g., due to transported pollutants). In this section, we focus primarily on the former situation. Section 4.5 addresses regional scale energy use and health impacts.

Large, developing-world cities are often characterized by rapid growth, increasing traffic congestion, the intermingling of industrial, commercial, agricultural and residential zones, and often inadequate sanitary

11 See Footnote 1 (p 263).

and solid waste disposal systems. In the absence of technology interventions, urbanization in this setting typically leads to higher outdoor air pollution concentrations (Smith and Ezzati, 2005), a substantial portion of which could be attributed to increasing energy use in buildings, transport, and industry as population and consumption rise. At the same time, household energy use for cooking and space heating may shift towards cleaner fuels and technologies, reducing indoor exposures from those sources. Depending on climate, development level, and fuel availability, building-related energy use for heating, cooling, lighting, and cooking ranges widely across and within cities in the developing world (Kandlikar and Ramachandran, 2000).

Income inequalities within developing-world cities may lead to large variations in exposures to, and resulting health impacts of, energy use for transport, buildings, or industrial production. Asthma and other chronic disease rates are on the rise worldwide, adding to vulnerability. In addition, children may be at special risk due to their activity patterns and developing respiratory systems (Selevan et al., 2000). Over coming decades, rapid population growth is likely to continue as people seek economic opportunities in cities. Technological interventions that reduce emissions per unit of energy used will be needed to avoid worsening health impacts. Recent successes in reducing transport emissions in Delhi and Dhaka serve as useful examples.

Most large cities in developed countries have relatively stable populations, adequate infrastructure for transport and waste disposal, and relatively stable or declining air pollution levels. Improvements in air quality are due in part to emissions controls and in part to slow economic and population growth rates. Per capita energy use in developed-world cities is high compared with developing cities, but low compared with the peri-urban communities that surround them. For example, a 2005 energy use survey reported that urban households use on average less than 80% of the energy used by suburban households in the United States (US EIA, 2005). Transportation and the heating and cooling of buildings are the two major categories of local energy use. In contrast to the situation in developing cities, industrial production is usually not a major energy sector in developed cities. Per capita transport energy demand varies considerably depending on urban density and the availability of public transportation. While pollution emissions per unit of energy used may be relatively low, population exposures can be elevated owing to high population density and the proximity of people to emissions sources, especially motor vehicles. High and increasing rates of asthma result in a large pool of vulnerable people. In the next few decades, continuing efforts to reduce energy use and pollution emissions have the potential to accelerate improvements in environmental health in large cities in the developed world.

Low-density, peri-urban communities (i.e., "suburbs") have been growing rapidly in developed countries for many decades (Frumkin et al., 2004). Residents of many such communities depend almost completely on automobiles for moving people between home, work, school, and commercial services. Thus peri-urban communities tend to have high per capita energy use for transportation. Because dwellings and other buildings are typically large, detached, and surrounded by high-maintenance landscapes, these communities also have relatively high per capita building-related energy use. Accordingly, emissions of pollutants from fuel combustion may be high on a per capita basis, but relatively low per unit of land area, resulting in lower ambient air pollution levels than in nearby cities. Local air pollution hot-spots may still occur where high-traffic roadways pass close to residences, schools, or other places where people congregate.

4.4.3 Community Health Risks From Energy-Related Air Pollutants

Fuels (including wood, coal, oil, gasoline and diesel, liquified petroleum gas, and natural gas) may be combusted in communities to supply energy for transportation, to heat and cool buildings, and for waste processing and disposal. Fuels may also be burned to produce electricity for lighting, though this combustion often occurs outside of city limits. In addition, solid fuels (e.g., dung, wood, charcoal, coal) are often used for cooking in developing-world cities. While the household impacts of solid fuel use for cooking are discussed above (see Section 4.2), here we consider the implications of solid fuel combustion for ambient air quality in urban areas.

Depending on the fuel used and the way it is burned, combustion may produce a wide spectrum of solid and gaseous pollutants that can impact community air quality. It is useful to distinguish between primary and secondary pollutants. Primary pollutants are emitted directly at the source and thus have the potential for very local air pollution health impacts. Secondary pollutants form via reactions of primary pollutants in the atmosphere and thus have the potential for wider, more regional impacts. Pollutants emitted within communities will be experienced by community members mainly as primary pollutants; communities downwind of the source are more likely to experience them as transformed secondary pollutants. Thus, isolated communities (i.e., those not downwind from many other communities) will be exposed mainly to primary pollutants generated locally. On the other hand, communities that are downwind of many other communities will experience both locally generated primary pollutants and transported secondary pollutants. As population and economic activity rise, the relative importance of secondary pollutants is likely to rise. Indeed, a relatively easy way to reduce local primary pollution impacts is to build taller smokestacks on industrial and power facilities, though secondary pollutant impacts in downwind communities may increase.

Primary pollutants emitted by fuel combustion include many of the "criteria" pollutants that are often measured and regulated (i.e., SO_2, NO_2, CO, and some of PM_{10} and $PM_{2.5}$, including lead if used as a gasoline additive), as well as many other less-familiar or less-measured "non-criteria" pollutants such as trace metals, elemental carbon, and a wide range of solid and vapor-phase organic compounds. Secondary pollutants include ozone, some components of PM_{10} and $PM_{2.5}$, and organic vapors. Among secondary particles, sulfates, nitrates, and organic and elemental carbon represent important components. The levels and character of the pollutants emitted from fuel combustion depend greatly on the type of fuel used, the conditions of combustion, and on any post-combustion pollutant capture technologies. Across these dimensions, communities tend to utilize cleaner options as economic development advances, which is likely an important reason for the trend towards lower community-scale emissions as one moves up the economic development scale (Smith and Ezzati, 2005).

Available knowledge regarding the effects on human health of the pollutants that derive from fuel combustion is robust for only a subset of these pollutants (Kunzli et al., 2010). The knowledge base is most extensive for the criteria pollutants, owing to their widespread measurement in developed countries. In developed-world cities, scientific evidence for health impacts at observed concentrations levels suggests that particulate matter (either PM_{10} or $PM_{2.5}$) and ozone remain of greatest concern among the criteria pollutants.

Laboratory studies have shown that ozone can cause acute, reversible drops in lung function, increases in non-specific bronchial responsiveness, and pulmonary inflammation (Kim et al., 2011). In addition, epidemiology studies demonstrate associations with worsened asthma, emergency room visits, hospital admissions, and deaths. In particular, time-series analyses have shown that ozone is associated with an increased risk of premature mortality. Daily changes in ambient ozone concentrations have been found to be significantly associated with daily changes in the number of deaths, on average, across 98 US communities. Any anthropogenic contribution to ambient ozone, however slight, presents an increased risk for premature mortality (Smith et al., 2009). NO_x, CO, or volatile organic compounds (VOCs) emissions can contribute to ozone concentration both near and far from emission sources. Populations most at risk include children and adults who are active outdoors, especially those with asthma.

Epidemiology studies addressing health effects of PM_{10} and $PM_{2.5}$ have reported associations with both acute and chronic mortality in urban areas, as well as increases in hospitalizations and respiratory symptoms and decreases in lung function. Long-term studies in the United States have found strong associations between human exposure to fine particulate matter and adverse impacts on human health, including lung cancer and deaths from cardiopulmonary disease (Pope et al., 2002). Time-series studies have found similar concentration-response relationships in the developing countries of Asia (HEI, 2010). Because recent research indicates there is no well-defined threshold below which adverse health impacts from PM do not occur (Schwartz et al., 2008), incremental increases in PM concentration can increase rates of premature death in relatively clean communities as well as polluted ones. Populations at greatest risk of PM effects include the elderly and those with pre-existing cardiopulmonary disease. Not yet clear from the available evidence is whether specific chemical components of PM are more important than others in the observed health effects.

Assessing health risks associated with energy-related air pollution emissions in communities is challenging. First, there are many relevant pollutants that cause adverse health impacts, and choices must be made as to which to include in the analysis. A common approach, particularly in developing-country settings, is to use particulate matter as a proxy for the entire mix of pollutants. This is a reasonable strategy, given the strong evidence base for premature mortality effects of PM. Another key challenge in developing countries is the limited availability of data – including air pollution exposures, baseline health statistics, and the exposure-response relationship linking pollution to health risk– for use in risk assessments. Also, not all air pollution in communities arises from energy use, so it can be challenging to parse out the energy-related component of health risk.

WHO tackled many of these challenges in its analysis of the adverse health burden related to urban air pollution for world cities with populations of 100,000 or more in the year 2000 (Cohen et al., 2004). This assessment used particulate matter to represent all urban air pollution, and estimated the numbers of deaths associated with $PM_{2.5}$ levels in each city as compared to a reference concentration of 7.5 ug/m^3. It focused on three categories of cause of death: cardiopulmonary and lung cancer deaths among adults, and acute respiratory infections in children from birth to age four. The largest mortality burden was estimated to occur in the more polluted, rapidly growing cities of the developing world. On a global basis, it was estimated that urban PM caused approximately 3% of mortality due to cardiopulmonary disease, about 5% of mortality from lung cancer, and about 1% of mortality from acute respiratory infections.[12]

Adult mortality attributable to $PM_{2.5}$ was estimated using a concentration-response function derived from the US-based American Cancer Society epidemiologic study (Pope et al., 2002). Since the effect of PM pollution was not well known above 50 ug/m^3 $PM_{2.5}$, mortality impacts were truncated at that level. In spite of these uncertainties, this work provided a valuable snapshot of the total health burden in 2000 attributed to urban air pollution, which totaled 0.8 million premature deaths annually. Note that not all outdoor fine particle pollution is due to the operation of energy systems; they are, however, probably responsible for about 85% globally.

As part of the current GEA effort, estimates of the global burden of years of life lost and DALYs due to ambient particulate matter in 2005 are calculated based on the WHO (2004) (Cohen et al., 2004) methodology using estimated exposures and most recent baseline mortality and DALYs from WHO (2008). Globally, there were 23 million DALYs and 2.75 million premature deaths due to outdoor air pollution from energy

12 As noted previously, this WHO assessment is being extensively revised for 2012 publication.

systems. These new estimates are higher than those reported earlier in the WHO work discussed above, due in part to higher pollution concentration estimates in China and India, but also because all exposures, urban and rural, were included. The reader is referred to Chapter 17 for a full description of this assessment. The distribution of estimated $PM_{2.5}$ levels is shown in Figure 17.45.

It is also worth noting that, when monetary values are assigned to the health damage caused by air pollution, the economic benefits of air quality improvements can be very substantial. Nemet et al. (2010) and colleagues reported that air pollution-related health co-benefits can substantially offset control costs for GHG emissions reductions.

4.4.4 Exposure vs. Emissions

An important consideration in assessing the potential health significance of air pollutants emitted by fuel combustion is the temporal-spatial relationship between pollutant concentrations and the people living in those communities. No matter how much pollution is emitted, people must breathe air pollution of sufficient concentrations for sufficient periods of time to elicit adverse health effects (see Box 4.1). Digging deeper, we may examine this question for population subgroups of potentially greater vulnerabilities, including the young, the old, and those with pre-existing diseases. Although clear understanding of which levels produce how much ill health in each population is not yet available, exposures that are higher and/or longer will be of greater health significance.

Spatial relationships between source and receptor can vary widely for different types of fuel combustion sources. Also, human activity patterns play an important role in determining the extent to which individuals encounter air pollution. In developing-world cities, for example, poor individuals often live in more polluted locations, and are more likely to commute by walking or cycling along congested roadways. People living in poverty are thereby exposed to elevated levels of air pollution, while also experiencing high lung doses due to enhanced activity and breathing rates. This is particularly true for children, who have higher metabolic rates than adults (Selevan et al., 2000). Wealthier individuals often live in cleaner neighborhoods and are more likely to commute by car, and their pollution doses may be lower due to less time spent on the roads and slower resting breathing rates. In developed-world cities and suburbs, similar patterns are seen, although a far greater proportion of the population commutes in vehicles. Housing design and climate factors influence the extent of penetration of ambient air pollution indoors. The intake fraction (Box 4.1) is a metric to integrate over these domains and provides a relative ranking of human impacts of different sources per unit of emissions. Kandlikar and Ramachandran (2000) estimated values of a related metric, exposure efficiency, for a range of sources across the development gradient. Exposure efficiency ranges from 100 Exposure Units [EU = (ug/m^3)-person-year] per tonne for a US power plant to 100,000–200,000 EU/tonne for indoor combustion in urban India.

4.4.5 Building-Related Air Pollution Emissions

Residential and commercial buildings are an important source of energy-related air pollution emissions in communities, due to the combustion of fuels for heating, cooling, and cooking. The nature and magnitude of the impacts on air quality vary with the type and amount of fuel used, how it is burned, the density of buildings, and local topographic and meteorological features. Emissions and local concentrations generally diminish as one moves from coal and wood to oil and to natural gas. Major air pollution episodes such as London's killer Great Smog of December 1952 have been attributed to dense, urban household coal combustion combined with stagnant "inverted" meteorological conditions, favoring the buildup of particulate matter and other pollutants in the lower atmosphere. Transition to oil and other clean fuels for household heating led to substantial improvements in air quality in London and other developed-world cities in the 20th century, essentially eliminating the periodic mortality peaks that had previously been observed. In Dublin, Clancy et al. (2002) documented a 10% drop in cardiovascular deaths and a 15% drop in respiratory deaths in the years following the 1990 elimination of household coal combustion. Black smoke concentrations in Dublin fell by about two-thirds following the coal ban. Oil is far cleaner than coal, and more refined grades of oil are cleaner than residual oil. Recent studies in New York have highlighted the pollution impacts of residual oil combustion for heating of buildings in winter and for hot water and steam generation throughout the year (Peltier and Lippmann, 2009). Peltier et al. (2008) show that commercial burning of residual fuel oil, mainly for space heating, leads to high concentrations of trace metals (e.g., nickel) that may have particular health significance.

In addition to fuel switching, technology improvements can lower emissions while also reducing energy use and GHG emissions. Many cities are developing GHG emissions inventories, and the building sector can be a dominant source of such emissions. For example, the 2005 New York City emissions inventory found that over 60% of CO_2-equivalent emissions were from residential, commercial, and institutional buildings (City of New York, 2007; Bloomberg and Aggarwala, 2008). Substantial health co-benefits can be achieved via technology strategies whose primary objective is to reduce GHG emissions, because they reduce air pollution emissions (Wilkinson et al., 2009). The monetary value of these health benefits could partially or completely compensate for the costs of the new technologies.

In developing-world cities, emissions from cooking with solid fuels like wood, dung, and charcoal contribute significantly to urban air pollution. The proportional use of wood and dung is usually lower in urban than in rural areas (Kandlikar and Ramachandran, 2000), but the density of emissions is far higher. In Africa, charcoal often becomes the dominant cooking fuel in urban areas. Though emitting fewer particles at the stove than wood, the production of charcoal in low-technology kilns is highly polluting, although fortunately usually occurring outside cities.

4.4.6 Transportation Emissions

Energy use for transport is a major source of air pollutants in all communities, but with wide variations depending on vehicle densities, congestion, fuels, and engine technologies. Vehicle emissions have special significance from a human health perspective because they occur in close proximity to people, enhancing the fraction of emissions that is inhaled. In developed cities, where industrial and uncontrolled point source combustion is relatively rare, vehicle emissions can be the dominant local air pollution source (Qin et al., 2006). The situation in developing cities is far more complicated, with much higher levels of air pollution emissions overall, from a wide range of sources. However, vehicles play an important and probably increasing role in urban air pollution in developing cities Kinney et al. (2011). In a study of four Indian megacities, Chowdhury et al. (2007) found that gasoline and diesel vehicle emissions together represented 20–50% of $PM_{2.5}$ concentrations, depending on the city and season.

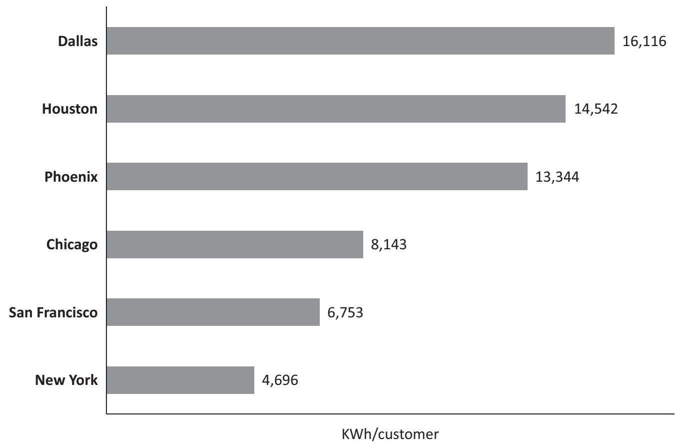

Figure 4.4 | Average annual residential electricity usage by city, 2000–2005. Source: adapted from City of New York, 2007.

Though there are few reliable data on vehicle emissions in developing cities, emissions per kilometer are estimated to be at least an order of magnitude higher than in developed cities, and perhaps far higher (Kandlikar and Ramachandran, 2000). Reasons for higher per vehicle emissions in developing countries include higher proportions of diesel vehicles, adulteration of fuels with inexpensive alternatives like kerosene, and the lack of catalytic control of engine emissions. Several large developing-world cities have achieved major air quality improvements by enacting laws requiring the use of cleaner fuels in commercial vehicle fleets (Chelani and Devotta, 2007; Begum et al., 2008; Reynolds and Kandlikar, 2008).

Reducing per vehicle emissions, either through fuel or technology interventions, is a relatively fast and economical approach for achieving significant improvements in urban air quality. Another challenging but ultimately more sustainable solution is to address growing road congestion by providing public transportation options. This has the potential to reduce the rapid rise in private vehicle use being seen in many developing cities, which is far outpacing road infrastructure (see Table 4.8). Many developing-world cities are examining urban transport reform, with some success stories (e.g., Brazil or Bangkok). Dedicated lanes for bus rapid transit can reduce both congestion and air pollution levels, while also providing affordable transportation for urban residents. Developed cities (e.g., London, Milan) have been successful at reducing congestion by imposing automated congestion fees within the downtown zone. While many developed cities are dependent on private vehicles for workforce commuting, there are wide variations even within countries. For example, the proportion of commuters using public transportation in six US cities ranges from 5% to over 50% (Figure 4.4).

Vehicles can affect air quality in other ways besides their engine emissions. Road dust can be a serious nuisance in developing-world cities, and often carries health risks due to toxic materials re-suspended with the dust, including asbestos from brake linings, lead from tire weights, and oil from leaking tanks.

Table 4.8 | Composition of vehicle population in India.

Year end March	Mopeds, Motorcycles etc.	Cars, Jeeps etc.	Buses	Goods Vehicle	Others	Total (Million)
	(as % age of total vehicle population)					
1951	8.8	52.0	11.1	26.8	1.3	0.31
1961	13.2	46.6	8.6	25.3	6.3	0.66
1971	30.9	36.6	5.0	18.4	9.1	1.86
1981	48.6	21.5	3.0	10.3	16.6	5.39
1991	66.4	13.8	1.5	6.3	`11.9	21.37
2001	70.1	12.8	1.2	5.4	10.5	54.99
2002	70.6	12.9	1.1	5.0	10.4	58.92
2003	70.9	12.8	1.1	5.2	10.0	67.01
2004	71.4	13.0	1.1	5.2	9.4	72.72
2005	72.1	12.7	1.1	4.9	9.1	81.5
2006	72.2	12.9	1.1	4.9	8.8	89.61

Source: Government of India, 2009.

4.4.7 Community Impacts of Transported Regional Pollutants Related to Energy Supply

As described below in Section 4.5, community air quality can be impacted by pollutants transported from other regions. In fact, upwind sources may often dominate local sources as contributors to community air quality, particularly for communities that are downwind of major source regions, such as cities in the northeastern United States, and those downwind of the industrial heart of China, such as Hong Kong. The scale over which pollution can be transported may be hundreds or even thousands of kilometers.

4.4.8 Energy-Related Pollutants in Water and Soils

Health can also be negatively impacted by energy-related pollutants in water and soils. Spills are common near oil drilling and handling operations. Spills from ageing or sabotaged pipelines have increased in Arctic Russia, the Niger Delta, and the northwestern Amazon, leading to contaminated drinking water supplies, fishing areas, and agricultural fields (Jernelov, 2010). In a preliminary analysis of health impacts in the months after the BP oil spill in the Gulf of Mexico, Solomon and Janssen (2010) report that 300 people sought treatment in Louisiana for symptoms typical of hydrocarbon and/or hydrogen sulfide exposures, including nausea, vomiting, cough, and respiratory distress. Mining has been associated with offsite contamination of domestic groundwater supplies, even after minesite reclamation (Palmer et al., 2010). Exposure can also come from contact with surface water (Besser et al., 1996) or re-suspended dust (Ghose and Majee, 2007). Hazardous compounds in dust were elevated near surface coalmining operations in India (Ghose and Majee, 2007). Elevated rates of cardiac, pulmonary and kidney diseases, and hypertension were observed in the general population living near coal mining operations in the US state of West Virginia (Hendryx and Ahern, 2008). Health damage from fossil fuel extraction processes can be reduced through improved mining practices, but also by efforts targeting energy demand, such as improved energy efficiency and use of renewable sources.

4.4.9 Other Sources

Other energy-related sources that can play an important role in community air quality include electric utility facilities (as well as smaller distributed energy sources), industrial operations, port facilities, and uncontrolled combustion of solid waste. The latter is a widespread source of toxic pollutants in developing cities. Though not strictly an energy issue, the energy contained in solid waste could be utilized for energy supply while at the same time improving air quality and health. Waste-to-energy facilities may represent a long-term solution to this growing problem.

Electric utilities and small power generators often are sited in or near urban areas. Depending on the fuel burned, stack height, and emission control technology employed, emissions and local impacts vary widely. Peak energy loads during summer hot spells are often supplied by diesel generators, with higher impacts than plants fired by natural gas. Large electric utilities require large amounts of water for their routine operations, and can adversely impact downstream water quality.

Industrial operations have been largely eliminated from developed cities but still remain significant sources of air pollution in many developing cities (Kandlikar and Ramachandran, 2000; He et al., 2002). While moving dirty industries away from populated areas would be the most sustainable solution, improved fuels and emissions control technologies can provide important short-term gains. There is also growing recognition of the air quality impacts on local communities of emissions from port operations (e.g., Newark, New Jersey; Los Angeles).

4.4.10 Conclusions

Air pollution emissions from fuel combustion are a major risk factor for morbidity and mortality in communities. Key energy-related emissions sectors include transportation, building heating, cooling and cooking, electricity generation, industrial processes, and waste combustion. Transportation emissions are particularly influential in health burdens, due both to the nature of the emitted pollutants and to the close proximity of emissions and vulnerable populations. Within and across communities, vulnerability to pollution-related health risks varies as a function of age and income. While health burdens due to community air pollution exist everywhere, these burdens are largest and in developing-world cities, particularly in China and India.

4.5 Regional and Transboundary Impacts

4.5.1 Key Messages

- Air pollutants can be transported long distances before being removed from the atmosphere and thus health impacts from emissions can occur locally, regionally, and even globally, following intercontinental

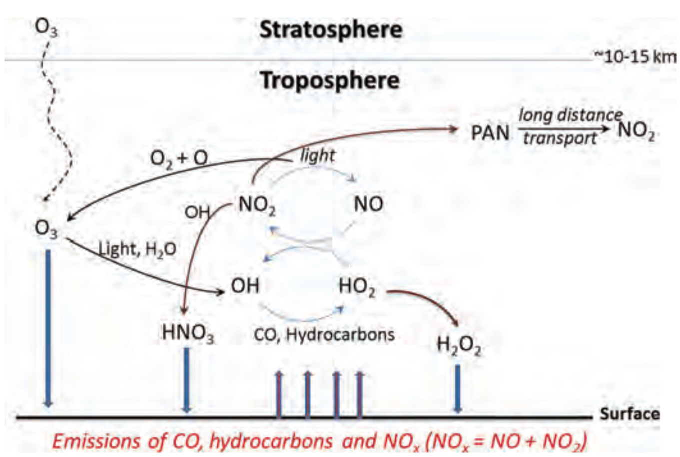

Figure 4.5 | Ozone production in the troposphere.

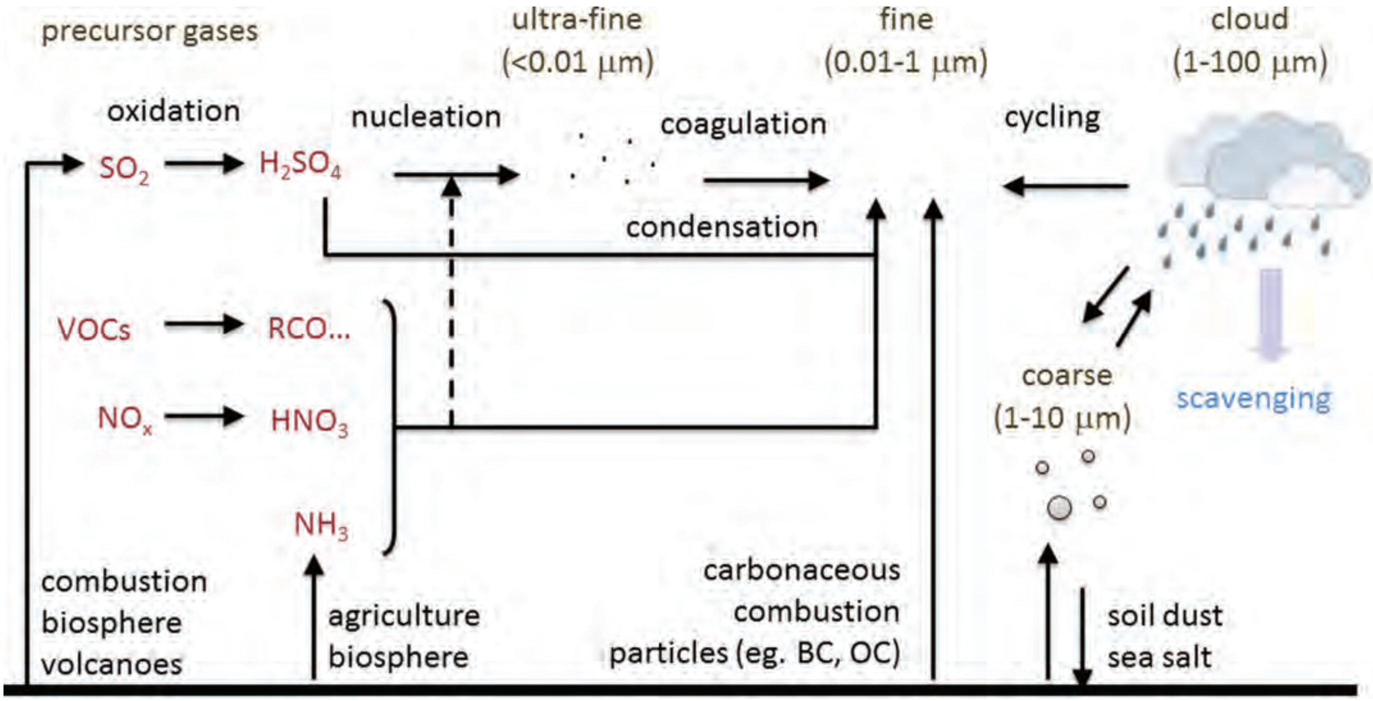

Figure 4.6 | Particulate matter (PM) sources and processes.

transport. In general, health damage due to ambient air pollution from the combustion of fossil and biomass fuels is greatest close to the source of emissions and within population centers.

- Emissions of particulate air pollutants have a significant effect on climate change. Externally mixed sulfate aerosols decrease radiative forcing, while black carbon (BC) aerosols increase it. Hence, although reductions in particle concentrations benefit public health, reductions in emissions of sulfur dioxide (the precursor to sulfate) will likely warm climate and reductions in the emissions of BC will likely cool climate.
- Long-range transport can bring black carbon to glaciers and snow-covered regions (Kopacz et al., 2011) where it may increase melting rates, affecting water supplies and health.

4.5.2 Contribution of Energy Systems to Air Pollution

Combustion of both fossil fuels and biomass releases a myriad of gaseous and particulate air pollutants in large quantities that have direct adverse impacts on public health. These pollutants include nitrogen oxides (NO_x); VOCs including methane, carbon monoxide (CO), sulfur dioxide (SO_2); and black carbon and organic carbon (OC) particulates. In addition, a variety of persistent organic pollutants (POPs) and heavy metals, including mercury (Hg), are also emitted. The reaction of some of these compounds in the atmosphere in the presence of sunlight forms secondary pollutants. In particular, NO_x, CO, and VOCs can react to form ozone (O_3) (see Figure 4.5). Sulfur dioxide and nitrogen oxides can form aerosols. (See Figure 4.6 for a summary of the sources and processes of particulate matter.)

The lifetime of air pollutants varies from hours (NO_x) to days/weeks (aerosols, VOCs) to months (O_3, CO, and Hg) and even years (POPs). The lifetime of the pollutant has a large influence on the distance it can travel before being removed from the atmosphere. Methane –produced by both natural and anthropogenic sources is released by the incomplete combustion of fossil fuels and, in larger amounts, as leaks from oil refineries, pipelines, coal mines, and other parts of energy systems – has a lifetime of approximately 12 years. As a result, it is relatively well mixed in the atmosphere. Oxidation of methane contributes to the production of tropospheric ozone. However, due to methane's long lifetime in the atmosphere, ozone may be produced far from the source of methane emissions, contributing to the observed rise in global background ozone levels (Fiore et al., 2008).

4.5.3 Mechanisms of Regional and Intercontinental Transport

Historically, air pollution was viewed as an urban problem. The Great London Smog of December 1952, caused by the combustion of coal, mainly for residential heating, during an atmospheric inversion that trapped the pollutants close to the surface, caused the death of thousands of people. This resulted in increased recognition of the toxic effects of air pollution on the urban scale.

In the 1970s, several studies confirmed that acid deposition could occur hundreds of miles from where SO_2 was emitted as a result of the oxidation of SO_2 to sulfuric acid (H_2SO_4) and sulfate. Starting in the 1980s, there was increasing recognition that other pollutants can be transported hundreds of miles and affect air quality far downwind of emission sources. The Long Range Transboundary Air Pollution Convention and its protocols (www.unece.org/env/irtap) were signed and ratified by nations of Europe and North America in the 1980s and 1990s to control emissions of sulfur, nitrogen oxides, VOCs, heavy metals, and POPs, and to abate acidification, eutrophication, and ground-level ozone concentrations. The Convention was the first international effort at coordinated abatement of air pollutant emissions.

In the late 1990s, efforts began in the United States to develop interstate emission controls on NO_x in order to reduce the long-range transport of ozone. NO_x emitted in cities and then transported to rural areas can react with VOCs emitted from vegetation to form ozone on a regional scale (see Figure 4.5). Elevated ozone concentrations can impact human health, ecosystems, and agriculture on a regional to global scale (Bell et al., 2004; Mauzerall and Wang, 2001).

Transport of air pollutants across the North American or European continent takes approximately one week, while circumpolar transport of pollution at northern mid-latitudes takes approximately one month. Mixing between the tropics and the high latitudes of the northern hemisphere requires approximately three months. Starting in the late 1990s, intercontinental transport of air pollutants, particularly ozone, mercury, and POPs, was recognized by the research community as potentially affecting the ability of some regions to meet their own air quality goals (Fiore et al., 2002).

Although aerosol transport from Asia to the United States has been observed by satellite as taking less than one week, average transport time is calculated to be two to three weeks (Liu and Mauzerall, 2005). Pollutants with lifetimes of a few days or less tend to remain within a limited area, while those with lifetimes of several weeks or more can cross oceans and influence air quality on downwind continents. Pollutants with lifetimes less than several years, however, have their largest concentrations close to the source of emission.

Intercontinental transport also influences surface ozone concentrations. Ozone has a lifetime of days in the continental boundary layer (the surface to approximately 2 km) but several weeks in the free troposphere (approximately 2–10 km above the surface). Ozone can be transported in the free troposphere and then subside to the surface, where it has adverse effects on human health, ecosystems, and agriculture. Observations at northern mid-latitudes have shown background ozone concentrations to be rising from preindustrial concentrations of approximately 10 ppbv (parts per billion by volume) (Marenco and Gouget, 1994). Model simulations define background ozone concentrations to be the ozone that results when emissions of ozone precursors from one region are turned off while emissions from the rest of the world are maintained at current levels. Present background concentrations in the United States are in the range 20–40 ppbv, at least half of which is of anthropogenic origin (Fiore et al., 2002). Rapid increases in combustion of fossil fuels for industry and vehicles in Asia has led to large increases in the emission of NO_x (Ohara et al., 2007) and resulting increases in hemispheric background concentrations of ozone, despite simultaneous decreases in NO_x emissions in the United States and Europe.

4.5.4 Implications of the Lack of a Threshold below which Air Pollutants No Longer Damage Health

As noted in Section 4.4, there is good evidence of health effects of small particles, even at low levels. In addition, both observational and modeling studies show that concentrations are influenced by long-range transport, as well as by local anthropogenic and natural emissions (Jaffe et al., 1999; Park et al., 2004). As a result, even relatively modest increases in PM concentration due to regional and intercontinental transport can increase rates of premature mortality in both polluted and relatively clean regions. A recent evaluation of the global health impact of intercontinental transport of fine aerosols found that nearly 380,000 premature deaths globally of adults age 30 and older are associated with exposure to particulates originating from foreign continents, with approximately 90,000 of these deaths attributable to fine, non-dust aerosols (Liu et al., 2009).

4.5.5 Effect of Ozone on Agricultural Yields

Episodes of elevated ozone are frequently observed in suburban and rural regions due to NO_x outflow from urban centers reacting with hydrocarbons from local vegetation. Elevated ozone concentrations can reduce agricultural yields (Mauzerall and Wang, 2001). Surface ozone in East Asia in 1990 is estimated to have reduced agricultural production of wheat, rice, and corn in China, Korea, and Japan by 1–9% and of soybeans by 23–27% (Wang and Mauzerall, 2004). In 2020, assuming no change in agricultural production practices, grain loss due to increased levels of ozone pollution is projected to increase to 2–16% for wheat, rice and corn and to 28–35% for soybeans (Wang and Mauzerall, 2004). More recent studies have examined the global impact of ozone on agricultural crop yields in the years 2000 and 2030 (van Dingenen et al., 2009; Avnery et al., 2011a; Avnery et al., 2011b), and found 2000 global relative yield reductions to be approximately 9–14% for soybean, 4–15% for wheat, and 2–6% for maize; in 2030, the projected yield losses were 5–26% for wheat, 15–19% for soybean, and 4–9% for maize. Similar results were obtained by van Dingenen (2009). Developing countries are likely to experience simultaneous increases in population and in emissions of ozone precursors, with resulting reductions in agricultural yields. This will have an indirect effect on health via escalating commodity prices, hunger, and malnutrition in some parts of the world.

4.5.6 Mercury Emissions: Transport and Intake that Affects Health

Mercury, largely emitted from coal combustion, has long been recognized as a global pollutant by the scientific community (Selin, 2005). Mercury is largely emitted in the elemental form Hg(0), which is oxidized in the atmosphere to Hg(II) and subsequently deposited. The atmospheric residence time of Hg(0) is about a year, which permits its global transport (Selin et al., 2007). Microbiological action converts Hg(II) into methylmercury (MeHg), an organic form of mercury. MeHg is highly toxic and can accumulate up the food chain in aquatic systems, leading to high concentrations in predatory fish. Consumption of contaminated fish is the major source of human exposure to MeHg in the United States. Fetal exposure via fish consumption by pregnant women can pose neurodevelopmental risks (NAS, 2000).

4.5.7 Effects of Air Quality on Climate Change and Vice Versa: Resulting Effects on Health

Some air pollutants have a significant effect on climate. As shown in Figure 4.7, tropospheric ozone and black carbon together have a positive global radiative forcing larger than methane, the second most important CAP (Forster and Ramaswamy, 2007). In contrast, sulfate and organic carbon have a negative radiative forcing due to both direct effects (reflection of incoming solar radiation) and indirect effects on clouds (smaller droplets and hence whiter clouds with higher albedo) (Forster and Ramaswamy, 2007). Table 4.9 summarizes the climate, health, and environmental issues associated with emissions leading to sulfate and BC (see also Box 4.2).

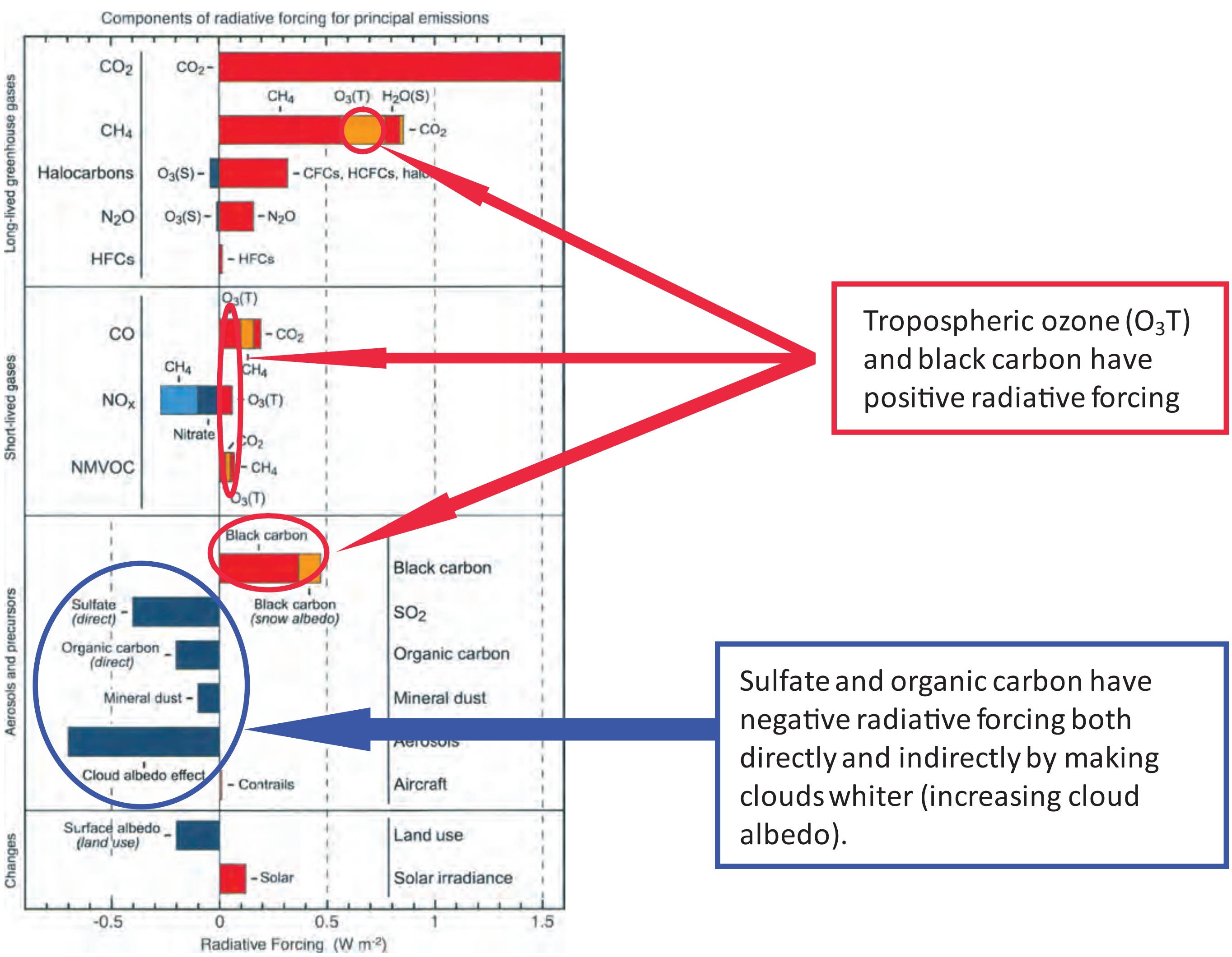

Figure 4.7 | Global radiative forcings due to emissions changes, 1750–2005: important contributions of air pollutants. Source: adapted from Forster and Ramaswamy, 2007.

Table 4.9 | Summary of sulfate and black carbon, climate, health, and environment issues.

	Source	*Measurement*	*Health*	*Climate*	*Environment*	*Confounders*
Sulfate	Mainly power and industry, but also transport	Little uncertainty although emissions are mainly SO_2 gas, with calculation of transformation to sulfate necessary	May be less damaging than the average PM, but uncertain	Relatively little uncertainty on direct and indirect climate cooling effects, but cloud physics still poorly understood	Acid precipitation – relatively little uncertainty but wide difference in impact by location	Sulfur control can reduce mercury emissions from power plants but has minor interaction with other types of control
Black Carbon	Mainly diesel engines and household fuel	Because BC is co-emitted with other carbonaceous aerosols basic measurement methods and metrics not well characterized	May be more damaging than the average PM, but uncertain	Major uncertainties but high radiative forcing – complicated by location and short lifetime	Major melting impact if falls on ice or snow, particularly in Arctic and Himalayan glaciers. Not well understood	Except for emissions from diesel engines, it's difficult to control BC alone without also reducing organic aerosol emissions, which are generally cooling

Source: Smith et al., 2009.

Box 4.2 | Health and climate primer for energy-related climate-active pollutants

Long-lived (hundreds of years)

Carbon dioxide (CO_2) poses a low direct health hazard and indeed is also the weakest greenhouse pollutant by mass. However, because of its magnitude of emissions, it is the most important overall. It also has a much longer lifetime in the atmosphere than any of the other energy-related pollutants – most is gone in 100 years or so, but a portion of emissions is thought to remain in the atmosphere for thousands of years. Even without special measures to burn fuels more cleanly, measures that reduce fossil fuel use or increase its efficiency will have co-benefits, through associated reduction of CO_2 emissions and the health-damaging pollutants noted below that accompany fuel burning. About 78% comes from the combustion of fuels.

Medium-lived (tens of years and thus globally mixed)

Methane (CH_4) is the second most important greenhouse pollutant. About one-third of global emissions come directly from energy-related sources, including leakage from oil/gas facilities and coal mines as well as incomplete combustion of biomass and fossil fuels. Its main sources, however, are from agriculture and poor management of wastes. Although not directly health-damaging, methane is a primary precursor to the global rise in tropospheric ozone levels. Although methane has a shorter atmospheric lifetime than carbon dioxide, a tonne of methane will have a much bigger warming impact than a tonne of CO_2 for the first few decades after emission, because of its large direct and indirect impacts on warming.

Short-lived (days to weeks, and thus effects depend on local conditions)

- Carbon monoxide (CO) is mainly a product of incomplete combustion. Although it does not have a direct climate effect, it acts to sweep up hydroxyl (OH) radicals in the atmosphere, thus effectively increasing the lifetime of methane and adding to tropospheric ozone. The impacts of CO on methane and tropospheric ozone are both potentially climate warming. About two-thirds comes from the energy sector, the rest from forest/savannah/agricultural fires.

- Non-methane volatile organic compounds (NMVOCs) come from several human-generated sources, including incomplete combustion and evaporation from fuels. They also have primarily indirect rather than direct impacts on climate. They play an important role in urban ozone formation as well. NMVOC emissions reduce the oxidizing capacity of the troposphere, increasing the lifetime of methane and adding to tropospheric ozone. Many of these compounds also have direct health effects on humans. About one-third is due to human energy use.

- Nitrogen oxides (NO_x) derive from fuel combustion and have a complex relationship with and indirect impact on both climate warming and cooling by affecting ozone, methane, and particle levels. NO_x emissions act to decrease the oxidizing capacity of the troposphere and increase the lifetime of methane, but also are a major precursor to tropospheric ozone. Nitrate particles, like those of sulfate, are lighter colored and thus generally cooling. There also seems to be a small increase in carbon capture in natural ecosystems due to the eutrophication from deposited nitrate. About half comes from the energy system.

- Sulfur oxides (SO_x), which derive mainly from combustion of fuels, partly convert to sulfate (SO_4^{2-}) aerosols in the atmosphere, which although potentially health-damaging, are generally thought to exert a net cooling effect on the climate. Along with organic carbon (OC, see below), can sometimes be coated with black carbon (BC, see below) to create "brown carbon" with warming potential. Essentially all human emissions derive from fuel use (see Figure 4.10).

- Black carbon (BC), which is fine particulate matter of dark color containing a large fraction of elemental carbon, is derived exclusively from incomplete combustion. They are strongly warming in the atmosphere and increase heat absorption if deposited on ice and snow, such as on Himalayan glaciers or in the Arctic. About two-thirds of human emissions come from energy systems (Figure 4.10).

- Organic carbon (OC) aerosol, which is less dark carbonaceous particulate matter produced, like BC, largely from incomplete combustion, but also from secondary processes involving biogenic VOCs. Although not well characterized and sometimes coated around BC, it is thought generally to produce a net cooling effect globally, although with much local variation. It is a major form of health-damaging small particles globally. About half comes from energy systems.

Very short lived (hours)

- Tropospheric ozone (O_3): is a secondary pollutant formed through complex photochemical reactions involving nitrogen oxides and volatile organic compounds including methane in the presence of sunlight. Worldwide, background ozone has more than doubled since pre-industrial times and continues to rise (Unger et al., 2008). Although plants and other natural sources such as forest fires contribute to ozone levels, the major sources are the rise in methane emissions and burning of fuels with subsequent increased emissions of nitrogen oxides and VOCs. In the Intergovernmental Panel on Climate Change (IPCC) assessments, as shown in Figure 4.7, taken all together, ozone is the third most important greenhouse gas (after carbon dioxide and methane), although itself created from other gases. Stratospheric ozone generally has different sources and, although also warming, protects Earth's surface from health- and ecosystem-damaging ultraviolet radiation.

Source: Smith et al., 2009.

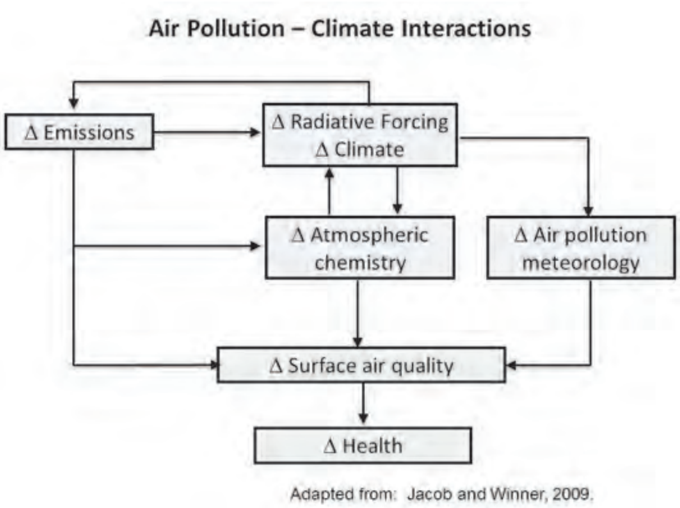

Figure 4.8 | Overview of air pollution – climate interactions from emissions to surface air quality to health. Source: adapted from Jacob and Winner, 2009.

Figure 4.8 summarizes interactions and feedbacks of air pollution, climate change, and health, which are in general poorly understood. Changes in emissions of CAPs affect radiative forcing and climate change (ozone, PM, methane), which in turn influences atmospheric chemistry, surface air quality (ozone and PM), and public health. Climate change affects meteorology and hence transport and mixing of air pollutants and natural emissions (biosphere, dust, fires, lightning) with implications for surface air quality (Jacob and Winner, 2009), health, and agricultural and ecosystem impacts. A recent study concluded that, "[c]oupled GCM (General Circulation Model]–CTM (Chemical Tracer Model] studies find that climate change alone will increase summertime surface ozone in polluted regions by 1–10 ppb over the coming decades, with the largest effects in urban areas and during pollution episodes" (Jacob and Winner, 2009). This climate penalty means additional impacts on public health unless stronger emission controls are implemented.

Sulfate, BC, and OC all contribute to suspended particulate matter less than 2.5 micrometers in diameter ($PM_{2.5}$). Figure 4.6 describes the sources and processes for forming, coagulating, and scavenging PM from the atmosphere (see also Box 4.2).

BC is emitted during the incomplete combustion of fossil fuel and biomass. BC is generally co-emitted with OC, another type of carbonaceous (carbon-based) aerosol. Because OC has a cooling effect on climate, the net warming effect of carbonaceous aerosol emissions decreases as their OC:BC ratio increases (Kopp and Mauzerall, 2010). This ratio is relatively high for biomass combustion and quite low for diesel engines. The warming effect of BC varies among source types and regions due to differences in co-emitted aerosols, transport, and deposition location. In addition to causing warming when lofted in the atmosphere, BC also enhances melting rates when it is deposited onto snow and ice. It thus contributes significantly to the warming of the Arctic, where it accelerates melting of sea and land ice. When it is emitted from South and East Asia, a major source area, it accelerates Himalayan glacier and snowpack melting, with resulting impacts on water supplies.

BC predominantly falls within the PM_{10} category (particulate matter with a diameter less than 1 micrometer). Both diffuse and concentrated BC particles, like all fine particles, have adverse impacts on human health, including premature mortality. There is a perception that particles from diesel engines, elemental, and organic carbon are the "most toxic" constituents of $PM_{2.5}$ (Cooke et al., 2007). The few long-term studies, however, do not indicate that BC particles are significantly more toxic than the "average" ambient particle (Smith et al., 2009).

As long as the BC/OC ratio is sufficiently high, reduction in emissions of combustion particles will result in rapid, short-term reductions in radiative forcing, hence slowing warming significantly in the near term while simultaneously improving public health (UNEP, 2011).

4.5.8 Conclusion

Poor combustion of both fossil and biomass fuels releases gaseous and particulate air pollutants in large quantities, nearly all of which have adverse impacts on public health. Pollutants with lifetimes of a few days or less tend to remain within a limited area, while those with lifetimes of several weeks or more can cross oceans and influence air quality on downwind continents. Because research indicates that there is no threshold of health effects at ambient concentrations of fine particulates, incremental increases in particle concentration due to regional and intercontinental transport can increase rates of premature mortality in both polluted and relatively clean regions. The secondary formation of ozone has direct adverse health impacts and also decreases agricultural yields, hence reducing food availability in some regions. Long-range transport of BC to glaciers may increase melting rates, thus influencing water supplies and health.

4.6 Global Health Impacts from Climate Change

4.6.1 Key Messages

- Of the many impacts of climate change on human health, most will be adverse and will particularly affect the world's people living in poverty and otherwise vulnerable populations. These health impacts will occur largely by exacerbating existing health problems. This will impede efforts to reduce longstanding public health impacts, particularly in low-income countries. Climate change will also confer some benefits to health in some populations, at least in the early stage of the process.

- There is broad agreement among researchers that, as climate change progresses, indirect effects on health are likely to account for the largest population health burden, compared to events with direct impacts such as heat waves. These indirect effects include the risks of malnutrition, altered patterns of infectious diseases, and the consequences of conflict, disruptions, and displacement due to climate-exacerbated resource shortages.

- The WHO's estimate of the burden of disease attributable to incipient climate change in the year 2000 identified malnutrition as the preeminent component of health loss. Most of that loss (i.e., premature deaths, stunting, and susceptibility to infection) was in young children in developing countries.

- The existing systems for managing public health problems should provide a foundation for CAP dealing with most of the health impacts of climate change. Therefore, it is likely that most of the required public health adaptations will entail incremental and complementary changes in those systems.

- Actions taken by governments and communities to reduce emissions should, in general, confer localized health benefits as a bonus (i.e., "health co-benefits"). This adds further incentive to undertake those mitigation actions.

4.6.2 Background

The science of climate change, including the influence of human use of energy, is now robust (see Chapter 3) and provides a base for anticipating and estimating human health consequences. Climate change affects social institutions, economic activities, and human health both directly and indirectly. Many major health problems in populations around the world, particularly in the poorer and more geographically vulnerable regions, are climate-sensitive. Hence, a change in climatic conditions will inevitably affect the rates and patterns of those diseases and disorders, including diarrheal disease, malaria, and under-nutrition – all

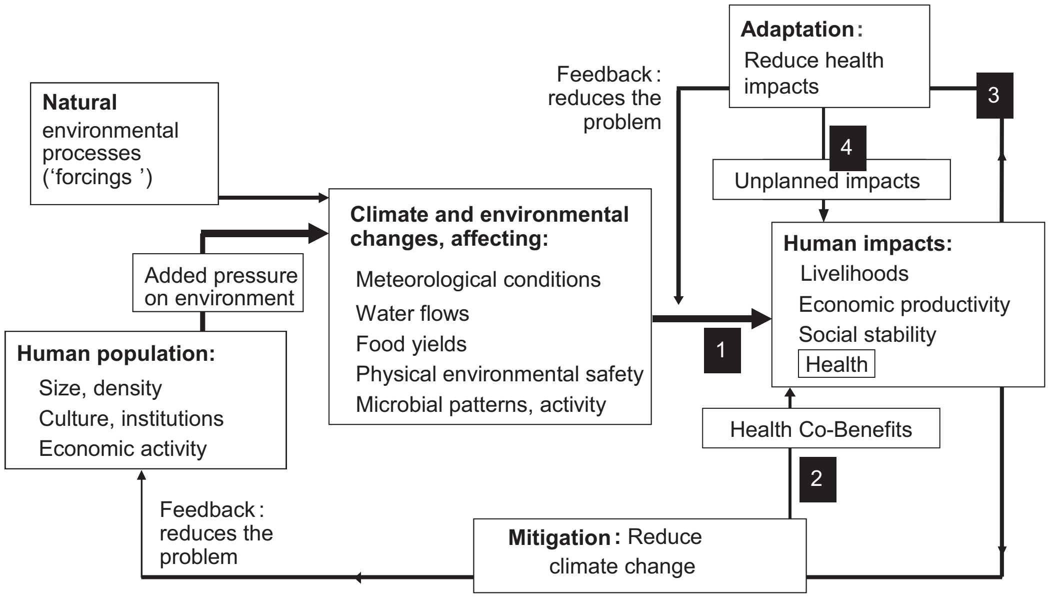

Figure 4.9 | Major pathways leading to impacts on population health associated with climate change and social responses. The four numbered paths refer to major, distinct, areas of research enquiry: 1 = identifying and estimating risks to health from climate change; 2 = estimating the collateral health benefits to local populations as they take action to mitigate climate change (mostly to reduce greenhouse emissions); 3 = research on the effectiveness and equity of adaptive strategies to protect population health against adverse climate change impacts; 4 = monitoring and estimating the collateral impacts of adaptive strategies on (mostly local) population health.

major killers of infants and young children in most low-income countries (Akachi et al., 2009).

Substantial inequalities in material and social conditions, and hence in health status and life expectancy, persist between subgroups, national populations, and geographic regions (Commission for the Social Determinants of Health, 2008). Many of these existing health inequities will be exacerbated by the environmental and social consequences of climate change. Climate-related exposures often impinge with differing intensity between locations (Kesavan and Swaminathan, 2006), and the resultant variations in adverse impacts on well-being, health, and survival will often be compounded by differences in human and financial resources, coping capacity, and social resilience.

The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) summarized the published scientific evidence, both direct and inferential, of current and future risks to human health from climate change (Confalonieri et al., 2007). It is not yet possible to confirm and quantify all of the many potential impacts of climate change on health. Those with limited available evidence include the risks to health from heightened (especially local/regional) food shortage and food insecurity, from sea level rise, and from population displacement and conflict. Further, climate change may cause widespread economic disruption, leading to severe health consequences – again, especially in poor and vulnerable populations (see also Costello et al., 2009).

Emerging evidence strongly suggests that some health impacts that are reasonably attributable to climate change have already occurred (Costello et al., 2009; McMichael and Bertollini, 2011). This evidence includes reports of an uptrend over recent decades in deaths, injuries, and other adverse health impacts from cyclones, storms, wildfires, and flooding; an increase in annual deaths from heat waves in several countries; shifts in the range and seasonality of some climate-sensitive infectious diseases; adverse mental health consequences in farming communities affected by drying; and impairment of food yields (and hence increased risk of malnutrition) in some already food-insecure populations. These are discussed in more detail below.

Recognition of the risks to human health strengthens the rationale for the rapid abatement of human-driven climate change (see Section 4.6). That is, those risks, properly understood, signal that climate change is beginning to weaken and disrupt nature’s life support systems – the systems that are prerequisite for the attaining and sustaining of high levels of human population health (Raven, 2002; McMichael, 2009a). Meanwhile, appreciation of the range and likely ubiquity of these health risks provides an evidence base for adaptive interventions to protect population health against those climate change-related risks that already exist or are apparently unavoidable, given the as-yet-unrealized climate change from extant emissions.

4.6.3 Diverse Health Risks; Multiple Causal Pathways

Weather variations and changes in climatic conditions affect human well-being, safety, health, and survival in many ways (see Figure 4.9). Some health impacts are direct-acting, familiar, and easily understood in relation to future climate change. This category includes the diverse health consequences of weather disasters (which will typically increase in frequency and intensity under climate change) and the health consequences of heat extremes within both the general community and segments of the workforce. Other health impacts are less immediate, occur via more complex pathways, and may be less obvious and more difficult to attribute (Butler and Harley, 2010). This category includes the changes in patterns of various infectious diseases, especially those transmitted via vector organisms, and the nutritional consequences of impairments in regional food availability, in part due to alterations in pests, aflatoxin contamination, and crop diseases (Butler, 2010). Climate change also harms ocean acidity (Doney et al., 2009), phytoplankton production (Boyce et al., 2010), and corals (Hoegh-Guldberg and Bruno, 2010).

Further, since climate change is part of a larger set of contemporary, human-induced global environmental changes, most of them of unprecedented scale, many of the health impacts of climate change will be modulated, and often amplified, by these other coexistent environmental changes. A ready example is that of food yields and human nutrition. In many parts of the world, the productivity of food systems is being jeopardized by the combination of soil exhaustion, chemicalization, diminished supplies of fresh water, local losses of biodiversity (e.g., pollinating organisms), coastal salination (rising sea level), and climate change (McIntyre et al., 2007).

Climate change entails a complex of environmental, ecological, and social changes. It is therefore not some new and distinctive "risk factor," nor is it likely to generate *new* diseases or health disorders. Instead, via that complex of changes, many existing population health problems will be exacerbated. It is important, in a policy context, to note that this threat of exacerbation heightens the already strong practical and moral rationale for reducing pre-existing disease rates as quickly as possible – something that the world is striving to achieve via the MDGs. An obvious focus of efforts to protect population health against further incursions by climate change is that of childhood malnutrition and infection, especially acute respiratory infection and diarrheal diseases, which currently kill around nine million children annually.

The following subsections consider first the health impacts of climate change that occur via apparently direct, relatively simple, pathways, followed by a discussion of those health impacts that arise via less direct, and often diffuse and deferred, causal pathways.

4.6.4 Direct Health Impacts: Temperature Extremes, Weather Disasters, and Health Impacts

Heat waves (extreme temperature events relative to local average, and of, typically, around three to seven days duration) will become more frequent and more severe as background temperatures rise and weather variability increases. It is well established that heat waves can kill people and increase the incidence of heart attacks and strokes, especially in the elderly, the frail, and those with underlying chronic diseases (Kovats and Hajat, 2008).

Temperature extremes that exceed physiological coping capacity also affect bodily functioning, mood, and behavior (Kjellstrom, 2009). This usually happens at temperatures above 30°C, depending on humidity, wind movement, and heat radiation. This has particular relevance to segments of the workforce exposed to extreme thermal stress. Poor people without access to household or workplace cooling devices are likely to be most affected, in hot, high-income countries as well as in hot, low- and middle-income countries. This climate change impact will primarily affect adults 20–60 years of age. Heat also affects other daily physical activities that are unrelated to work for all age groups.

Physically active workers in low- and middle-income tropical countries are particularly vulnerable, since many are engaged in heavy physical work, outdoors or indoors, without effective cooling. If high work intensity is maintained in excessively hot workplaces, serious health effects can occur, including heat stroke, organ damage, and death. Meanwhile, depending on the type of occupation, the required work intensity, and the level of heat stress, as temperature extremes rise over time, working people will need to work more slowly to reduce internal body heat production and the risk of heat stroke. Hence, without preventive interventions to reduce heat stress on workers, both their individual health and economic productivity will be impaired (Kjellstrom et al., 2009).

Hotter weather also increases the formation and concentration of various noxious ambient air pollutants, especially ozone, in large, motorized, industrial cities. Ozone is a well-established risk factor for respiratory tract damage and cardiovascular disease. Much of the huge mortality excess caused by the August 2003 heat wave in Western Europe may have been due to the coexistent high levels of ozone in and around some of the big cities – high levels that, indeed, may have been partly attributable to the unusually high temperatures (Dear et al., 2005; Kinney, 2008).

Weather disasters – such as the cyclones that have struck vulnerable, mostly poor, coastal populations of Myanmar, Haiti, and Viet Nam in recent years – kill, injure, dispossess, impoverish, and cause mental health burdens. They also predispose people to outbreaks of infectious diseases and cause damage to crops. Among vulnerable populations, droughts variously cause hunger, loss of farming jobs, impoverishment, population displacement, and misery; suicide rates may rise in response to these hardships.

4.6.5 Direct Health Impacts: Sea Level Rise

The average global rate of sea level rise is now approximately 3 mm/year (Rahmstorf et al., 2007; Allison et al., 2009) – that is, approximately 50% higher than in the 1980s. A growing proportion of the rise is due to the melting of polar ice and (less certainly) alpine glaciers, on top of the contribution from the ongoing thermal expansion of ocean water. Increasingly, scientists expect that the sea level may rise by a meter or more this century (Hansen, 2007; Allison et al., 2009) – a figure that is noticeably higher than the cautious forecast contained in the IPCC's Fourth Assessment Report in 2007 (IPCC, 2007b). Well over 20 million people along the vulnerable coastal regions of Bangladesh, Egypt, and Nigeria are estimated to be at risk of inundation from a one-meter sea level rise, without also factoring in the inevitable population growth (Perch-Nielsen et al., 2008).

Sea level rise is already endangering food yields, freshwater supplies, and physical safety in several low-lying small island states (Barnett and Adger, 2003; Kelman, 2006; White et al., 2007). In some cases, these problems are exacerbated by high population density and continuing high fertility rates (Ware, 2005). India, with its low-lying and densely populated coastline extending for over 7000 km, is highly vulnerable to sea level rise. This includes the threat of inundation and salinization of many coastal paddy fields (Kesavan and Swaminathan, 2006). Various less direct risks to health (physical and psychological) will result from likely displacement of populations and the breakup of families and communities due to sea level rise.

4.6.6 Indirect Pathways

The health of human populations depends fundamentally on various environmental and ecological systems and processes that determine the cycling and flow of water, food yields, and the natural geographic and seasonal constraints on infectious agents. As human-induced climate change progresses, these essentially indirect pathways are likely to account for an increasing and substantial proportion of the population health burden attributable to climate change (Confalonieri et al., 2007; Costello et al., 2009; Butler and Harley, 2010). These impacts will occur particularly via increased malnutrition, altered range and seasonality of infectious disease, and the consequences of conflict, social disruptions, and displacement due to resource shortages.

4.6.6.1 Water Insecurity

Climate change will exacerbate water insecurity in many regions, via alterations in the seasonality and intensity of rainfall, via geographic shifts in rainfall systems, and by increased rates of evaporation. As is evident in the paleoclimatic record, global warming displaces rainfall systems in subtropical regions towards the poles. Such displacement appears to have emerged recently in southern Australia, southern Africa, southern Canada, southern Spain, and Italy, for example. Further, stratospheric ozone depletion, as a concomitant global environmental change, also contributes to such displacement of rainfall systems (Cai, 2006).

By 2050, the projected changes, from medium-to-high scenarios of climate change, in rainfall, surface runoff, and depleted flows from reduced glacier masses will expose an estimated additional 2–3 billion people to severe water stress (IPCC, 2007a). Water scarcity poses multiple risks to health, including water-borne infectious diseases (e.g., cholera, other diarrheal organisms, cryptosporidium, etc.), vector-borne diseases associated with water storage, exposure to higher concentrations of salt and chemical contaminants in water, and impaired food yields. Sufficient water also reduces the risk of water-washed diseases, including diarrhea (Curtis and Cairncross, 2003), trachoma (Mecaskey et al., 2003), and scabies. Water stress seriously constrains sustainable development, particularly in savannah regions, which represent two-fifths of the world's land area. It may also lead to conflict over diminishing supplies, as well as the many adverse health consequences that flow from conflict, property loss, bereavement, and population displacement (McMichael and Bertollini, 2011).

4.6.6.2 Food Yields, Food Insecurity, and Health

Many aspects of climate change and its environmental consequences affect food yields, on land and at sea. Impairment of food yields by climate change, including the impacts of an increase in extreme weather events and heightened risks of infestations and infectious diseases, pose a great threat to population health. Meanwhile, food insecurity persists widely, and appears to have increased in absolute numbers over the past decade. In 2009, over one billion persons were classified as undernourished (FAO, 2009), representing around a one-fifth increase on the corresponding estimate at the start of the decade (Butler, 2009).

During 2008, as food prices escalated and shortages emerged, concerns were expressed about contributory climatic influences on food yields (Sheeran, 2008). Indeed, climate change is increasingly viewed as a likely contributor to altered food yields in many regions (Lobell and Field, 2007; Lobell et al., 2008; Battisti and Naylor, 2009). This superimposed threat to food supplies from climate change looms greatest in food-insecure regions where high levels of malnutrition and child stunting already exist (Lobell and Field, 2007).

Modeling studies consistently project that climate change will, overall, have a negative impact on global food yields (Nelson et al., 2009). However, those impacts will occur unevenly; some temperate regions may benefit, particularly where the soil is fertile. In general, countries in the tropics and subtropics, where both warming and reduced rainfall are likely to occur, are at greatest risk. Many studies indicate that South Asia is particularly vulnerable, and likely to experience declines in total cereal grain yields of the order of 10–20% by later this century (Fischer et al., 2005). In temperate regions and at high latitudes, agricultural productivity could initially increase, but elsewhere smallholder and subsistence farmers, especially in the tropics, are at particular risk (Morton, 2007).

Many such model-based estimates are likely to be conservative, particularly since they are unable to take into account the episodic, perhaps "surprise," events that will greatly increase the damage to yields and harvests. Extreme weather events (storms, floods, fires, etc.) can wreak disaster. This happened in 2010 with the extreme wildfires in Russia, which, in combination with preceding prolonged drought, resulted in the loss of almost one-third of the nation's annual wheat crop. Climatic conditions also affect the probability of damage by plant and livestock pests and pathogens. The northern movement of the blue-tongue virus in Southern Europe, in association with warming over the past decade, has extended the region of an economically catastrophic threat to cattle and sheep populations (Purse et al., 2005). Warming affects a range of pests; flooding favors fungal growth, whereas drought encourages aphids, whiteflies, and locusts.

It is clear from the above that estimating the current and future contributions of climate change to local or regional food availability per capita is necessarily an inexact and incomplete science. There are further methodological difficulties in translating food availability into an estimation of the actual burden of disease and functional impairment (including intellectual development in children) due to malnutrition. One major reason is the considerable variation in the role of climatic conditions as direct determinants of food availability, as well as other factors in the causation of stunting and wasting, such as diarrhea, tropical enteropathy (Humphrey, 2009), and other infections.

In remote and food-insecure regions, climate-related downturns in yields of crops and pastures can quickly result in hunger, under-nutrition, starvation and, on occasion, conflict. For example, a field assessment in western Sudan by the United Nations Environment Programme (UNEP) concluded that tensions between traditional farmers and nomadic herders over declining pasture and evaporating water holes, during a protracted period of declining rainfall, may have contributed to recent conflicts (UNEP, 2007). Inevitably, the cause of such conflict is complex (McMichael, 2009a). Other authors have noted the lag of several decades between a stepped decline in rainfall in the region and the outbreak of conflict, and have assigned a primary causal role in the region discrimination against the population of Darfur by the central Sudanese government (Kevane and Gray, 2008).

Concerns over the risk of conflict due to the environmental consequences of climate change should be set against other evidence indicating that genuine cooperation can eliminate conflict (Salehyan, 2008). Indeed, care should be taken to ensure that the implication of environmental factors is not used to evade political responsibility for the occurrence of conflict (Butler, 2007). Nevertheless, many examples from human history suggest that the long-term prospect of conflict arising in part from resource insecurity, both real and perceived, is genuine – especially when a tipping point is exceeded. Unabated climate change will reduce many kinds of resources, including food, fertile coastal land, and habitable areas within low-lying cities. The nurturing of protective human institutions to reduce this threat is vital – but so, too, are the technological developments and the forms of social reorganization that are required to accelerate the energy and sustainability transitions (Walker et al., 2009).

4.6.6.3 Infectious Diseases

Many infectious diseases – whether food-borne, water-borne, or vector-borne – are sensitive to climatic conditions (Dobson, 2009; Wilson, 2009). Various combinations of warmer temperatures, increased rainfall (affecting both humidity and surface water bodies and flows), changes in wind patterns, altered profiles of vegetation, and the aftermath of weather disasters can affect a wide variety of infectious disease agents, vectors, and the pathogen's intermediate (non-human) host species.

The rate at which bacteria multiply in food and in nutrient-loaded water increases as temperature rises. Research in Australia and elsewhere has shown a clear positive relationship between weekly or monthly temperatures and the incidence of (reported) salmonella food poisoning (D'Souza et al., 2004; Kovats et al., 2004). Changes in rainfall can affect local flooding, well-water quality, river flows and general sanitary conditions, thereby affecting the spread of diarrheal diseases, including cholera. Research based on extensive systematic historical records in southern India shows that cholera outbreaks occur most often either when conditions are very dry (and vibrio bacteria are therefore concentrated) or during times of flooding and crowding when person-to-person contact increases and hygienic conditions deteriorate (Ruiz-Moreno et al., 2007). Furthermore, especially in temperate and tropical areas, flooding can lead to increased moulds in and around dwellings, and hence additional respiratory illnesses such as asthma (Rao et al., 2007).

The range and seasonality of many vector-borne infections (diseases transmitted by mosquitoes, other insects, or rodents) are sensitive to temperature, rainfall, humidity, and wind. Pathogens incubating within mosquitoes (e.g., the malaria plasmodium and dengue virus) mature and replicate more rapidly as temperatures rise (within limits – excessive heat is harmful to insects, as it is to humans); and mosquitoes feed more frequently (McMichael, 2009a). Minimum temperature is often particularly important, often as a threshold. As predicted by climate change modeling, minimum daily temperature has been rising more rapidly around the world in recent decades than has maximum daily temperature.

Surface water patterns influence mosquito breeding; humidity and temperature affect mosquito survival. Modeling vector-borne disease transmission shows that a small temperature rise can substantially increase transmission probability. Hence, where the geographic range of malaria has increased alongside gains in climate-determined suitability the geographic range of for transmission – as in parts of eastern Africa recently – it is reasonable to assume that the climate trend partly explains the observed increases in disease (Pascual and Bouma, 2009).

The occurrence of infectious diseases (many of them vector-borne) that spill over sporadically into human populations from animal sources – that is, 'zoonotic' infections – is often influenced by climate-related changes in the population density and geographic range of the "reservoir" animal species (Harley et al., 2011). Examples include: West Nile Fever (now in the United States and Canada: host animal species are birds), bubonic plague (sub-Saharan Africa, western USA, Central America: wild rodent species), Lyme disease (south-eastern Canada: deer), Ross River Virus (Australia: kangaroos and wallabies), and Rift Valley Fever (Kenya: cattle).

In recent years, the geographic range of some vector-borne infectious diseases appears to have increased in association with documented regional warming (Alonso et al., 2011; McMichael and Lindgren, 2011). The explanation for any one, disease-specific observation is usually contestable. However, the overall pattern, across multiple settings and continents, indicates the likely emergence of a climate "signal." This set of changes includes shifts in patterns of occurrence of malaria in some eastern African highlands, tick-borne encephalitis in Sweden and the Czech Republic, and Lyme disease in Canada.

Recent warming in eastern China has been accompanied by the northwards extension of the temperature-limited transmission zone for schistosomiasis (for which the temperature-sensitive water snail is intermediate host), putting an estimated 21 million more persons at risk (Zhou et al., 2008).The first reported outbreaks of dengue in the Himalayan foothills have occurred recently – in Bhutan in 2004 and in Nepal in 2006 (TDR, 2009). Meanwhile, in Europe, there has been recent evidence of warming-induced northwards extensions of the bluetongue virus disease in livestock, and of its midge vector (Purse et al., 2005). In 2006, a further northerly extension occurred, with an outbreak 900 km north of its previous limit (Carpenter et al., 2009).

4.6.7 Social, Economic, and Cultural Disruption and Health

The disruptive effects of climate change on social conditions, relationships, and economic circumstances will affect human health and well-being in many ways. For example, adverse impacts on freshwater supplies and food yields can cause social and economic disruptions. These, in turn, may result in the displacement of people, which then often leads to various health risks, including malnutrition, mental health problems, and exposures to infectious diseases.

These direct and indirect risks to health may be further amplified by accompanying changes to other health-related behaviors, such as the (economic) need to resort to transactional sex, or by increases in the consumption of tobacco, alcohol, and perhaps illicit drugs. An illustration of the complex and sometimes extended pathways by which climate change may increase the burden of disease is in relation to HIV/AIDS (see Figure 4.10).

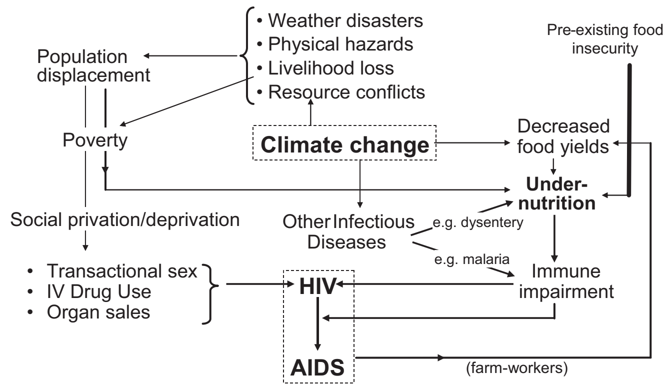

Figure 4.10 | Multiple pathways for impacts of climate change on risks of HIV/AIDS.

This category is also well illustrated by the impacts of the relatively rapid ongoing warming in the Arctic region. The resultant loss of sea ice and permafrost is already adding further stress to already disturbed traditions of living, hunting, and eating patterns in the Inuit communities of northern Canada. One consequence has been a reduction in physical activity, an increased reliance on imported energy-dense processed foods, and hence potentially amplified risks of obesity, cardiovascular disease, and diabetes (Nickels et al., 2005). The mental health consequences of these social and cultural disruptions, and of associated perceptions of future threats, pose an increasingly important risk to health.

4.6.7.1 Population Displacement

In addition to the above-mentioned general health risks associated with population displacement, changes in climate will often intensify the stresses and health risks of displacement and may erode environmental resources at the site of resettlement.

Estimates vary as to the likely number of persons displaced by climate change, with mid-century totals often of the order of several hundred million (McMichael and Bertollini, 2011). Much climate change-related displacement is likely to occur in developing regions where public health resources are lacking or inadequate (Carballo et al., 2008). Increased flooding, water shortages, and drought are likely to amplify rural-to-urban migration in many such countries, yet many poor urban communities are situated in parts of cities that are themselves at high risk for climate change impacts. Hence, people migrating into these settings may face continued environmental and, hence, health threats.

4.6.8 Burden of Human Disease Attributable to Climate Change

The task of risk assessment and risk estimation, in relation to either current or future climate change, is a very heterogeneous one; it depends on type of health outcome, type of population, and the time of interest (present or future). Some estimations are relatively straightforward; for example, for a given plausible temperature increase, and with no future change in population biomedical profile nor in adaptive circumstances, how will annual age-specific death rates from heat waves change?

Identifying and quantifying the climate-attributable impact on various other specified population health outcomes (e.g., child stunting due to malnutrition) are inherently difficult, especially at the relatively earlier stages of climate change. The often diverse, coexistent non-climate influences, upon the same health outcomes, of cultural attributes, behaviors, and exposures can easily obscure any early real signal of a climate-related health impact. Child stunting is, for example, influenced by many factors other than agricultural production or even food intake. These include co-infection with parasites, caloric demand due to ambient temperature and workload, and the frequency of other infections, including malaria, diarrhea, and tropical enteropathy (Humphrey, 2009).

Another area of difficulty relates to estimating how and how much climate change affects mental health – a health risk in many of Australia's rural communities, for example, who face increased warming, drying, and fires; declining incomes; and possible future relocation. Similarly, inhabitants of low-lying coastal areas and many small island states live with the growing insecurity, somewhat analogous to people who live in river valleys, that they are destined for future inundation (Jackson and Sleigh, 2000).

It is possible, however, to estimate the health impacts of climate change via statistical modeling, given sufficient prior knowledge of exposure-response relationships. Indeed, such an exercise was carried out in the early 2000s as part of a systematic international CRA project. That project estimated and compared portions of disease burdens (globally and regionally) attributable to a nominated list of major risk factors, including climate change. The estimation for climate change (McMichael et al., 2004) was necessarily limited to just the few health outcomes for which there was sufficient direct epidemiological evidence (from at least several geographic regions for each outcome) to derive an estimated average exposure-response relationship. The five such conditions were: diarrheal disease, malaria, malnutrition, deaths due to flooding, and (in developed countries) cardiovascular events and deaths due to thermal stress.

The modeling of attributable disease burdens from those specific health outcomes was carried out both for the year 2000 and for various future years (including 2020 and 2030). The best estimate of the average exposure-response relationship was derived from published literature. That relationship was then applied, using the estimated region-specific level of climate change "exposure" for 2000, and 2030 (from global climate models), to the project-generated estimates of current and future disease burdens from the health outcomes of interest. The modeling thus yielded estimates, at both the global level and by geographic region, of burdens of (chronic/disabling) disease and premature mortality attributable to climate

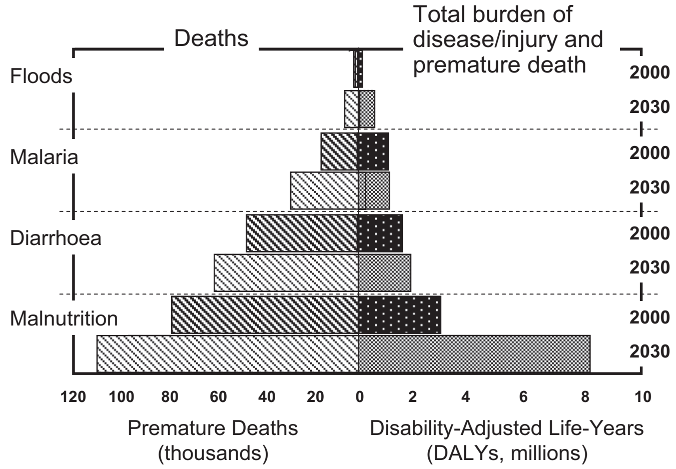

Figure 4.11 | Deaths and total burden of disease/disability/death attributable to climate change for the four selected health outcomes shown, in the years 2000 and (projected) 2030. Climate change is assessed relative to the average (reference) climate during 1961–1990. Estimations were done by major geographic region, in relation to region-specific estimates of climate change (2000 and 2030) and then summed. Estimates for 2030 were based on the projected region-specific disease and death rates for the year 2000. Source: data based on McMichael et al., 2004.

change that had already occurred by 2000 (or was projected to occur). These were expressed and summed as total loss of DALYs.[13]

The main results for the global level are summarized for 2000 and 2030 in Figure 4.11. The exercise yielded a modest estimate of the climate change-attributable burden of disease for the year 2000 (~0.4% of DALYs; 0.3% of deaths). Inevitably, that small figure reflected the marginal change in world climate over the course of the preceding several decades. In addition, only a few health outcomes that also had great relevance to the developing world (where the brunt of the impacts from malnutrition, infection, and flooding would be expected) could be included. An estimated 88% of the climate change-attributable loss of DALYs worldwide (and more than 85% of deaths) was in children under age five in poor countries. In 2000, the climate change-attributable burden of disease was estimated to increase by around 35%, compared to 2000, with a global population increase of only 25%. Malnutrition was considered to be responsible for the largest fraction of this burden, and also to have the greatest proportional increase. Beyond that time, population growth will further slow but the impact of climate change is likely to be disproportionately more, perhaps 40–50% greater than in 2000. Many synergies are likely; for example, heavier rainfall events that cause flooding, drowning, injury, and psychological trauma also contribute to diarrhea, reduced harvests (and resultant food prices rises), social disruption, and outbreaks of vector-borne diseases, including malaria, in some locations. Poor communities are likely to have the highest burden of disease, but high-income countries will not be fully spared.

13 The DALY was developed for this international assessment as a universally applicable metric enabling the project to provide the first-ever systematic assessment of disease burdens, within which comparisons could be made across risk factors, ages, sexes, and regions.

Box 4.3 | Mitigation and adaptation actions: Implications for health risks

If mitigation is to *avoid the unmanageable* (the types of changes and risks to health that would be seriously different, worse and perhaps uncontrollable, compared to current conditions), then adaptation is to *manage the unavoidable* risks to health (i.e., those that have already begun to occur, that are impending and probably unstoppable as further climate change occurs, or are fully realized with the physical, biological, and social environments).

Reducing emissions of climate-active pollutants (i.e., "mitigation") is the first-order task. Many mitigation actions will, in their own right, affect the health of localized populations; encouragingly, most of those consequences should be beneficial, and they are thus sometimes called "co-benefits" (see Section 4.10).

Adaptive strategies are also needed, however, given that no feasible mitigation measures can fully prevent human-caused climate change. Some strategies will entail improving or extending existing policies and practices, such as mosquito control, better sanitation, nutritional supplementation programs, and stronger flood controls. Others will require innovative actions, such as community-wide early warning systems for impending weather extremes (e.g., heat waves, storms, and cyclones), crop substitution, water harvesting, and (if feasible) genetic modification of mosquito populations (McMichael, 2009a).

Unless international cooperation and resultant mitigation actions increase markedly, the need for adaptive responses to lessen the impacts on health will stretch into the distant future. However, any such extended and prolonged reliance on adaptation – particularly if seen as a substitute for mitigation – would increase the moral dilemma, since adaptation will, in general, be more achievable and affordable in the higher-income countries (McMichael, 2009a). To constrain the risks to health (and to other environmental and social assets), to do so in the framework of *sustainability*, and to facilitate the achievement of a more equitable world, mitigation must remain the centerpiece of national and international climate policy.

The above comparative risk assessment exercise is almost a decade old. It may well be that its estimates for future health impacts are too conservative. For example, world food prices reached a fresh peak in 2010. A rising trend of extreme weather events, contributed to by climate change, appears to be a major cause of this peak. Higher food prices inevitably harm the nutrition and health of the poorest on a very wide scale.

4.6.9 Differences in Vulnerability

The adverse health impacts of climate change today primarily affect low-income, poorly resourced, and geographically vulnerable populations – just those who have not contributed historically to GHG emissions (Patz et al., 2007). This pattern will persist as climate change intensifies (Confalonieri et al., 2007; Costello et al., 2009; McMichael and Bertollini, 2011). Many of the low-income countries in tropical and subtropical regions, especially their poor slum-dwelling populations, will be at particular risk. Bangladesh, for example, is vulnerable on multiple counts: widespread poverty and food insecurity, high rates of infectious diseases associated with tropical climates and with poverty and crowding, a low-lying coastal population vulnerable to cyclones and storm surges (Mitchell et al., 2006), and threats to river water flows (Himalayan glacier retreat and the probability of upstream damming and diversion of rivers by China and India).

Higher-income countries also can have marked differences in vulnerability. In the United States, for example, the impacts of the 1995 heat wave in Chicago (Semenza et al., 1996) and the 2005 Hurricane Katrina in New Orleans differed markedly between ethnic and socio-economic groups. In Australia, the population groups considered to be particularly vulnerable to climate change include (McMichael et al., 2009):

- rural communities exposed to long-term drying conditions;
- older and frailer persons, especially in relation to heat waves;
- coastal communities facing storm surges, coastal erosion, and greater risks from cyclones;
- remote indigenous communities facing heat, drying, water shortages and loss of traditional food species; and
- persons living in regions where climate-sensitive infectious diseases may tend to spread, including communities in northern Australia with greater exposure to mosquito-borne infections.

In principle, for reasons of both moral obligation and achievable social benefit, adaptive strategies should be weighted towards high-vulnerability groups and subpopulations. In practice, such interventions could take many forms, depending on the scale (global, regional, local), the type of health risk, the timeframe, and the resources available. This has implications for the ways in which intervention options are selected, and the level of specificity at which they are evaluated.

Meanwhile, human-induced climate change is already occurring and will increase over the coming decades, no matter what action humankind takes today. Therefore, adaptation is required, at least transitionally, to reduce otherwise unavoidable adverse impacts on health. This will be particularly important in populations where underlying disease rates (e.g., child diarrhea, malnutrition) are already high and will therefore rise further due to multiplier effects caused by a change in climate (Smith and Desai, 2002).

Many adaptive strategies to reduce health risks require planning and coordinated action across diverse research disciplines, sectors of government, and community interests. This collaboration extends beyond the skills and experience of the formal health sector – and reflects the fact that a society's ways of building, moving, living, producing, sharing, and consuming are the prime determinants of population health. The typical 'health' sector plays a more limited, focused, and mostly reactive role to states of health and disease. However, in addition to joining the above collaboration, there remains a major distinct role for the health sector in adaptation strategy. Institutions (hospitals, ambulance services, etc.) will need added capacity to cope with impacts of more severe weather disasters. Health professional education and training should incorporate new learning about climate-related health risks likely to apply within any particular population. Public health programs such as vaccination, child nutrition, sanitation, and community education will require further fortification. Primary health care, as the front line of the health, will be important in educating, counseling, and detecting changing health outcome patterns (Smith, 2008).

4.6.10 Climate Change and Health: Attuning Public Health Capacities

Climate change will affect human health by modulating (mostly intensifying and extending) existing climate-related risks to health. Novel health outcomes are unlikely. Therefore, the existing social and public health systems should provide a foundation for the strengthening of adaptive strategies, via incremental and complementary changes in existing health risk management programs (Ebi et al., 2006; McMichael, 2009b). Such changes also include:

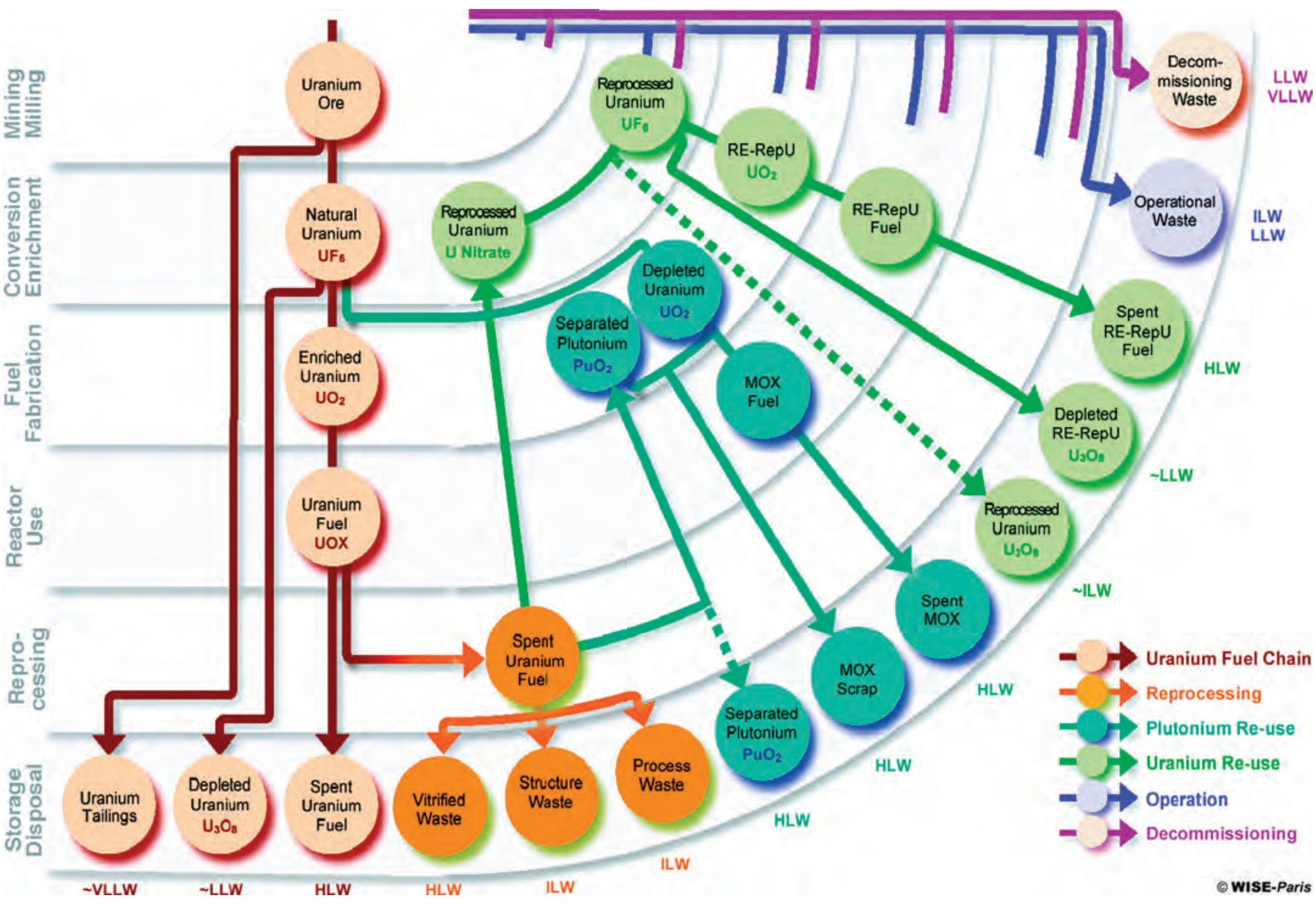

Figure 4.12 | The nuclear fuel chain. Source: WISE-Paris.

- Orienting the existing structure, staffing, knowledge base and awareness of the health system and its infrastructure to the altered and impending risks to health needs (Jackson and Shields, 2008)
- Translation of policies and knowledge from other countries or regions, to address changes in the geographic range of some health risks and diseases
- Restoration and strengthening of surveillance, maintenance and prevention programs that may have been neglected or abandoned
- Development of new policies and strategies to address any apparently new threats to health

4.7 Routine Health Impacts of the Nuclear Power Fuel Chain

4.7.1 Key Messages

- Based on current evidence, the main health effect from routine radiation releases from nuclear power facilities is the increased incidence of childhood leukemia – a rare disease. The resulting burden of disease is small compared to routine operation of fossil fuel facilities, but child cancer garners considerable public and policy concern.
- Radioactive releases from reprocessing plants are greater than from reactors. In addition, concerns exist about the significant environmental effects of uranium mining and milling which are often excluded from assessments of nuclear power.
- Average radiation doses to full-time permanent workers in nuclear power industries have generally declined over the past two decades. An increasing share of the collective dose is received by the workers of subcontractors and operators of fuel chain facilities.
- As with large hydroelectric facilities, there are difficult-to-quantify risks due to high-consequence low-probability accidents that affect workers and the public, which are also difficult to compare with day-to-day impacts (see Chapter 14).

4.7.2 Overview

The nuclear fuel supply system, from uranium mining to radioactive waste disposal, is frequently called the nuclear fuel "cycle." A strategy that leads to the direct disposal of spent fuel is referred to as "open" or "once-through," while a reprocessing strategy that separates plutonium and uranium from fission products and other wastes is called a "closed fuel cycle."

The use of such terminology suggests a circular system that confines most of the materials. In fact, each step in the system leads to specific radioactive and chemical emissions and specific new waste streams. A more accurate term would be the nuclear fuel "chain." In a typical light water reactor, with a direct disposal scheme (i.e., no reprocessing), the uranium is mined and milled before it is converted into uranium hexafluoride (UF6). In this gaseous form, the percentage of the fissile isotope U-235 is increased by diffusion or centrifugation. It is then converted back to uranium oxide, shaped into fuel pellets, and inserted into tubes in nuclear fuel assemblies. After the fuel has undergone fission in a reactor for three to four years, it becomes "spent" and is put into cooling ponds, in most cases, for at least 10 to 20 years. The term "spent" is slightly misleading, as this fuel remains extremely radioactive and dangerous for hundreds of years. The ultimate fate of spent fuel is a vexed issue and remains unresolved at this date. In many countries, spent fuel is being left in cooling ponds for increasingly lengthy periods due to the absence of technical solutions and to political opposition to plans for nuclear waste facilities. This unsafe and unsatisfactory situation poses considerable challenges for future nuclear waste management.

The decision to separate plutonium and uranium from spent fuel in reprocessing plants greatly increases the complexity of the system and its impact on the environment and health (see Figure 4.12). For these reasons, most future plans for nuclear power do not include reprocessing. (See Chapter 14 for more discussion.)

4.7.3 The Nuclear Fuel Chain

This assessment of the health impact of nuclear power systems distinguishes between effects on workers and the public. Average doses to workers in nuclear countries have generally declined over the past two decades. However, a larger share of the collective dose is received by workers of nuclear subcontractors and operators of fuel chain facilities. In France, for example, in 2008 about 31% of the nuclear workers under radiological surveillance belonged to subcontractor companies, but they received around 49% of the collective dose (calculation based on IRSN (2009)).

In 2005, a retrospective study (Cardis et al., 2005) on over 400,000 nuclear industry workers in 15 countries, the largest study of nuclear workers ever conducted, concluded that there were increased risks of solid cancers and leukemia, "even at the low doses and dose rates typically received by nuclear workers in this study" (Cardis et al., 2005). This finding is consistent with other studies of radiation health effects at low doses (NRC, 2006).

4.7.4 Uranium Mining and Milling

Canada, as the world's largest producer of uranium, illustrates issues in these stages of the nuclear fuel chain. After mining, uranium is separated from its ore by acidic leaching, as occurs in many uranium mines around the world. Because the ore usually contains only about 0.1%

uranium, leaching results in extremely large volumes of mine wastes. Canadian mine companies, for example, had accumulated about 213 million tonnes of uranium mine tailings (LLRWMO, 2004) and 109 million tonnes of waste rock, as of the end of 2003. In addition, this process has generated about 400 million cubic meters of contaminated process water. The resulting tailings, waste water, and runoff from waste rock piles contain over 80% of the initial radioactivity in the ore, and thus constitute serious low-level, but long-lived, radioactive hazards.

In addition, as in other types of ore processing, large volumes of sulfuric acid are used to mobilize heavy metals such as copper, zinc, nickel, and lead, which are highly toxic to aquatic and terrestrial wildlife. Severe contamination of groundwater constitutes a permanent risk. The government health ministry, Health Canada, states: "There is a serious possibility that the food chain can be contaminated unless appropriate mitigation is instituted. Fish, wildlife, vegetation, country foods, and drinking water are all at risk should spills or leakages occur. The need to manage the water from waste management areas is important, particularly if there are drinking water sources in the vicinity" (Health Canada, 2004). However, leakages, mostly small, do occur frequently. In the Elliot Lake area in Ontario, for example, over 30 failures of tailings dams have been reported.[14]

Recent research suggests that the health detriments of ingested and inhaled uranium may be greater than previously estimated, mainly because of the likely synergism between the carcinogenic chemical and radiation effects of uranium exposures (UNIDIR, 2008). There is also evidence that, like many other chemicals, uranium may have an endocrine-disrupting function in the body, implying that those exposed should be followed for increased risk of fertility problems and reproductive cancers (Raymond-Whish et al., 2007). As a result of such evidence, the German government recently decided to lower the regulatory limit to 10 micrograms of uranium per liter of drinking water (Associated Press, 2008).

The most significant health impacts from uranium mining probably result from the release of radioactive radon gas, which is particularly significant in underground uranium mines. Various studies have documented significant excesses in lung cancer among uranium miners (e.g., NRC, 1999; Grosche et al., 2006).

4.7.5 Uranium Conversion and Enrichment

The health risks associated with uranium conversion and enrichment are primarily due to the inhalation or ingestion of uranium in various chemical and physical forms. The uranium concentrate from the milling process (U_3O_8), which is termed yellowcake, is converted into uranium hexafluoride (UF_6), a highly volatile and toxic chemical. Airborne UF_6 immediately reacts with water vapor to form hydrofluoric acid, which is extremely toxic and can cause pulmonary irritation, edema, corrosion of the lining of the lungs, seizures, and even death.

The large stockpiles of depleted uranium accumulated as a byproduct of uranium enrichment, over 700,000 tonnes in the United States alone, pose challenges for future safe management. Depleted uranium is presently stored in ageing UF_6 containers at the sites of the enrichment plants, mostly in the United States. The conversion back to more stable uranium oxide involves the same type of risks as the original conversion from oxide to UF_6.

4.7.6 Nuclear Power Reactors and Nuclear Reprocessing Plants

During normal operation, nuclear power reactors routinely release radioactive gases to the atmosphere and radioactive liquids to the sea or rivers. In addition, when reactors are depressurized prior to being opened for refueling, larger gaseous emissions occur over short time periods. The main radioactive releases are tritium (hydrogen-3, half-life of about 12 years), carbon-14 (5,700 years), krypton-85 (11 years), argon-41 (1.8 hours), and a number of iodine isotopes (including iodine-129, 16 million years).

Commercial nuclear fuel reprocessing is carried out primarily in the United Kingdom and France. During reprocessing, spent but still highly radioactive nuclear fuel is cut up and dissolved in boiling nitric acid. Plutonium and uranium isotopes are then separated out from the fission products in the fuel. The recovered plutonium is fissile and can be used in nuclear weapons. Beyond the environmental and safety problems, it therefore constitutes a serious security and proliferation risk and is stored in guarded vaults. Part of the plutonium is mixed with uranium oxide to form mixed oxide (MOX) fuel, which is used in some reactors in Europe. However, the use of this fuel entails several economic, operational, and waste management disadvantages. (See Chapter 14 for more detail.)

The recovered uranium has no commercial value as it is contaminated with isotopes (U-234, U-236) that make further use unattractive. Most of it is currently stored in steel drums in the United Kingdom and France or has been exported to Russia. The remaining fission products, mainly cesium-137 and strontium-90, are stored in solution at high temperatures in dozens of huge tanks. These tanks, containing large unstable quantities of radioactivity, require continuous cooling by various independent cooling systems. Originally, these wastes were to be vitrified online and stored in the safer and more manageable solid form. However, such processes have proved complex and some of these (and future) wastes have remained in liquid form for many years. Again, this situation poses challenges for future nuclear waste management.

Annual nuclide releases from reprocessing plants are several orders of magnitude larger than those from nuclear power stations (European

14 This is not new. Thirty years ago, the Ontario Royal Commission on Electric Power Planning stated that, "The mining and milling of uranium ore produces very large volumes of long-lived, low-level radioactive tailings which have leached into waterways in the vicinity of Elliot Lake, Ontario, thereby posing serious health and environmental problems" (Ontario Royal Commission, 1978).

Parliament, 2001). The main releases are krypton-85, hydrogen-3, carbon-14, and a number of iodine isotopes (European Parliament, 2001). The global collective dose resulting from the discharges of the La Hague reprocessing facility for its remaining years of operational life – truncated[15] at 100,000 years – would cause over 3,000 additional cancer deaths globally, if the linear no-threshold theory of radiation is applied.

Although nuclides are routinely released from nuclear facilities, the health consequences among populations living downwind remain a subject of controversy. In the 1990s, several studies found increased incidences of childhood leukemia near UK nuclear facilities. However, official estimated doses from released nuclides were too low, by two to three orders of magnitude, to explain the increased leukemias. Recent epidemiological studies have reopened the child leukemia debate. Baker and Hoel (2007) carried out a meta-analysis of 136 nuclear sites in the United Kingdom, Canada, France, United States, Germany, Japan, and Spain and found cancer death rates for children were elevated by 5–24% depending on their proximity to nuclear facilities. Hoffmann et al. (2007) found 14 leukemia cases between 1990 and 2005 in children living within 5 km of the Krümmel nuclear plant in Germany, significantly exceeding the 0.45 predicted cases.

Most important, however, is the KiKK study, (*Kinderkrebs in der Umgebung von Kernkraftwerken* = Childhood Cancer in the Vicinity of Nuclear Power Plants) (Kaatsch et al., 2008; Spix et al., 2008) which found a 60% increase in solid cancer risk and a 120% increase in leukemia risk among young children living within 5 km of all German nuclear reactors. The findings are significant because KIKK was a large, scientifically rigorous study: the German government, which commissioned it, has confirmed its findings. The KiKK results are presently the subject of much research and it is too early to provide a firm explanation for the increased cancers although radiation exposures are thought to be involved. One hypothesis (Fairlie, 2009) proposes that infant leukemias are mainly a teratogenic effect from in utero radiation exposures due to radionuclide intakes during pregnancy. Whatever the explanation(s), the epidemiological evidence points to raised cancer risks among children living near nuclear reactors.

In recent years, a number of official reports have been published on the hazards of tritium, the radioactive form of hydrogen that is released in large quantities from all nuclear facilities, in particular from spent fuel reprocessing plants and heavy water reactors. Extremely large amounts of tritium would also be released from any fusion facility, should one ever be operated successfully. In the past, this isotope had been regarded as being only weakly radiotoxic, but this view is now changing among governments and international agencies concerned with radiation exposures. Reports have been published to date by radiation safety agencies in the United Kingdom (AGIR, 2007), Canada (CNSC, 2010a; CNSC, 2010b), and most recently in France. The French Nuclear Safety Authority (ASN, 2010) has published a comprehensive white paper on tritium and the French Institute of Radioprotection and Nuclear Safety (IRSN, 2010a; IRSN, 2010b; IRSN, 2010c; IRSN, 2010d; IRSN, 2010e; IRSN, 2010f) has published six major reports on tritium. These reports draw attention to various hazardous properties of tritium, including its extremely rapid distribution in the environment and its heterogeneous distribution within tissues.

15 The authors of the present report consider that, while the use of truncated collective doses might be justified in some comparisons, untruncated collective doses are necessary to treat present and future generations equally, a key requirement of the principle of sustainable development. Untruncated doses are of course larger than truncated ones.

4.7.7 Decommissioning and Waste Management

The collective dose of atmospheric discharges during the decommissioning processes of nuclear facilities in the European Union in 2004 have been estimated to be nearly 100 times less than from the operation of nuclear facilities (European Commission, 2005).[16] In total today, however, both are small by comparison to other human-caused radiation exposures, which are currently dominated by medical procedures and radon in buildings (Culling and Smith, 2010; see also Section 4.9).

Nuclear waste storage and disposal has led to significant environmental pollution in the past. In France, the Centre de Stockage de la Manche (CSM) repository stores 527,000 cubic meters of low- and intermediate-level waste and was filled and closed in 1994. The CSM contains considerable amounts of long-lived radioisotopes, including at the minimum about 100 kg of plutonium and 200,000 kg of uranium. It also contains large amounts of heavy metals, including about 20,000 tonnes of lead and 1,000 kg of mercury. Tritium leaks from the site have polluted the local water tables and streams. Contamination levels measured near the site exceeded six million becquerels per liter in 1983. Similar problems have been raised in Germany concerning the Asse nuclear waste disposal site that, in addition, is struggling with massive water intrusion and structural instability. The Federal Radiation Protection Office has recently recommended taking out all of the 126,000 drums with radioactive waste.

High-level waste (HLW) in the form of spent nuclear fuel or vitrified waste from reprocessing contains more than 90% of the radioactivity in wastes from nuclear electricity generation. However, there is no operating HLW repository in the world, and none is expected in the foreseeable future. This means that estimates of the radiological impacts of HLW disposal remain highly speculative, but HLW still poses the key question of intergenerational liability and justice. Although unlikely to pose health risk to populations approaching that of fossil alternatives, the difficulty of assuring the long-term integrity of HLW disposal sites and the difficulty of siting them due to local opposition is a major bottleneck to expansion of nuclear power in some countries (see Chapter 14).

16 These collective dose estimates were truncated by the European Commission at 500 years.

4.7.8 Transport

As can be seen from Figure 4.12, the nuclear fuel chain involves many stages, which inevitably results in a great deal of transportation between the various steps. These include uranium ore mining, milling, leaching, yellowcake production, U-235 enrichment, fuel fabrication, reactor operations, defuelling, temporary storage of spent fuel, encapsulation of spent fuel, and final disposal of spent fuel. This is for the direct once-through path; the reprocessing path involves significantly more stages.

Few recent studies have examined the routine health impacts of these transportation stages, as opposed to the health impacts of transport accidents that, by their nature, are not routine. Perhaps the most likely step where radiation doses may be a matter for consideration is the transport of spent nuclear fuel, in particular spent plutonium fuels (MOX fuels) by ship, rail, and road from reactors to reprocessing facilities. Older studies indicate that members of the public can receive small radiation doses from prolonged standing near spent fuel railway flasks. The result has been, at least in the United Kingdom, that railway transports of spent fuel are not allowed to stop in areas to which members of the public may have access or where they may be present.

4.7.9 Summary

Nuclear power facilities have been associated with the risk of some cancers in selected sub-populations, such as workers, but nevertheless do not represent a significant fraction of radiation exposure or the burden of disease in any population. Leaving aside the important potential of weapons-grade material being diverted from commercial nuclear fuel systems and major nuclear accidents, all major studies indicate that well-run modern nuclear power systems pose much less risk than fossil power systems, even modern ones. Nevertheless, because of the character and history of radiation, the risks of nuclear power systems are of particular concern to the public and policy makers and thus do significantly influence energy policy decisions in many countries. In addition, as the size and scale of nuclear facilities expand, such risks may also rise unless careful measures are taken. Finally, as discussed in Chapter 14, the difficult-to-quantify risks of proliferation from some nuclear fuel technologies may overwhelm those from all other parts of the system, including routine operation, accidents, and waste disposal.

4.8 Emerging Energy Systems

4.8.1 Key Messages

- Energy derived at a large scale from sunlight and wind is not free of health and environmental impacts. Issues of land use, maintenance, materials inputs, and energy storage raise concerns about environmental, occupational, and community health impacts.
- The health and environmental impacts of advanced materials such as nanotechnology materials that are used in some advanced energy technologies are not well characterized. There are a number of concerns about both occupational and environmental exposures from the widespread use of these materials and the resulting impact on disease burden

4.8.2 Background

Accessible and affordable energy has facilitated the industrialization, strengthening, and growth of the world economy over the past century. But rising energy use has also brought recognition to the human health and environmental impacts of different systems for producing, transforming, transporting, and consuming energy. As fossil fuel use developed over the last century, a variety of associated health and environmental effects began to appear. To address these problems, ongoing investments have been made in alternative energy sources and technologies, often with an implicit assumption that alternate sources will reduce impacts relative to existing technologies. The flaw in this assumption, however, is that lack of knowledge about impacts is not the same as absence of impact.

Changes from one energy source to another are likely to have different impacts through the whole usage chain (or fuel life cycle), from resource capture through to conversion, distribution, and end use. Moreover, because the full impact burden of extant energy systems has not been adequately characterized, there is no appropriate baseline against which to compare the relative benefits of new systems. Therefore, as world leaders consider options for changing the portfolio of future energy sources, it is important to examine each of the options for associated impacts and strategies to address those impacts.

The history of technology development (e.g., pesticides, vaccines, drugs, nuclear power, transportation, fuel additives) reveals that all technologies have both benefits and drawbacks (health, environmental, financial, and social). Not all benefits and drawbacks can be accurately characterized in advance of technology deployment, but technology assessment has proven useful in avoiding strategic errors that can derail a promising technology. Prior to widespread technology deployment is the time to confront issues such as demands on resources and materials, occupational and environmental health burdens, impacts on water supply and climate, and land-use offsets. As emerging energy technologies move from concept to deployment, there is a need to go beyond a simple current carbon benefit or net energy balance assessment and include other impacts such as human health benefits and impacts.

One tool to evaluate the cumulative impacts of existing technologies and anticipate the impacts of future technologies is lifecycle assessment (LCA). LCA provides a framework for comparing services and products (or product-related emissions) according to their total estimated environmental impact summed over all chemical emissions and activities associated with the product's life cycle. Box 4.4 below illustrates life-cycle impact as it applies to both existing and emerging energy systems.

Box 4.4 | Life-cycle assessment

Life-cycle assessment (LCA) has evolved over the last three decades as an effective strategy for organizing a comprehensive assessment of energy system impacts. The purpose of LCA is to quantify and compare environmental flows of resources and pollutants (to and from the environment) associated with an industrial system, such as an energy supply and use system, over the entire life cycle of the system – from resource extraction to energy use. LCA evaluates a broad range of requirements and impacts for technologies, industrial processes, and products in order to determine their propensity to consume natural resources or generate pollution. The term "life cycle" refers to the need to include all stages of a process – raw material extraction, manufacturing, distribution, use, and disposal, including all intervening transportation steps – so as to provide a balanced and objective assessment of alternatives. In the case of electrical energy, this means tracking the system from resource extraction (i.e., collection of sunlight, extraction of tar sands, collection of wind energy, etc.) through conversions, storage, transmission, and end use. In the case of transportation energy, LCA tracks the system of resource extraction (biofuel production, oil shale extraction, oil well production, etc.) through conversions, storage, and transport to the point of energy release and use in a vehicle (auto, bus, train, airplane, etc.).

An LCA includes three types of activities: collecting life-cycle inventory data on materials and energy flows and processes; conducting a life-cycle impact assessment (LCIA) that provides characterization factors to compare the impacts of different product components; and life-cycle management, which is the integration of all this information into a form that supports decision making. As an illustration of the LCA approach, Figure 4.14 shows a comprehensive LCA for transportation biofuels that addresses cumulative impacts to human health and the environment from all stages, impacts from alternative materials, and impacts from obtaining feedstocks and raw materials.

"To assess human toxicity impact, the LCIA practitioner considers for each chemical involved the cumulative exposure associated with the mass released to a defined (indoor, urban, regional, etc.) environment by multiplying the release amount by a measure of toxic impact to characterize the likelihood of health effects and their potential consequences. The SETAC Life Cycle Impact Assessment (LCIA) Working Group on Human Toxicity (Krewitt et al., 2002) has classified measures of toxic impact into two broad categories: potency-based characterization factors that are used to assess the likelihood of a disease or effect (cancer, death, reproductive failure, etc.) and severity-based characterization factors or damage factors that, in addition to the qualitative or quantitative likelihood of disease, reflect population consequences of the disease in terms of years of life lost or some other measure of societal impact" (McKone et al., 2006).

Below we discuss a set of emerging energy systems, along with the new and/or potentially worrisome health issues surrounding these systems. The health impacts from energy systems include those that can be measured through occupational or community health tracking and those that are estimated using tools such as risk assessment. Most of the health impacts from emerging systems, and many of the health impacts from existing systems, are in the latter category. So, a key challenge of addressing health impacts from emerging systems is the lack of large empirical databases or well-established assessment methods. To address this gap, we first consider the baseline impact from existing systems and then consider how emerging systems will perform to reduce and/or redistribute this burden.

4.8.3 Baseline Impact Assessment

For both transportation fuels and electricity production, an assessment of the current disease impact associated with a base metric, such as 100,000 vehicle km traveled and with a GWe-yr of electricity produced, provides baselines for the comparative assessment of emerging energy systems. It is difficult to obtain accurate and consistent assessments of the disease burden of energy in these terms, but some key studies offer insight regarding the magnitude of the disease burden. In its extensive study of energy externalities, the US National Research Council (NRC) (2010) noted that among alternate approaches employed to address baseline assessments, some are "top-down," others "bottom-up." The top-down approach makes use of morbidity and mortality statistics for a specific population, such as the inhabitants of a country or a population group, and postulates a link to a specific source, such as transportation or power plant emissions or to an activity (smoking). The bottom-up approach begins with hazard identification, defining sources for pollutants of concern and then follows these sources from a point of release into a receptor population to assess exposure and damage. According to the NRC (2010), "Top-down assessments for air pollution have been carried out for many regions such that it is possible to provide a disease burden estimate for air pollution. But allocation to specific energy

Table 4.10 | Examples of the categories of impacts that have been associated with pollutant emissions from energy supply and the specific types of health effects and other damages associated with these pollutants.

Impact Category	Pollutant/Burden	Effects
Human health – mortality	PM_{10}, SO_2, NO_x, O_3	Reduction in life expectancy
	Benzene	Cancers
	Benzo-[a]-pyrene	
	1,3-butadiene	
	Diesel particles	
	Noise	Loss of amenity, impact on health
	Accident Risk	Fatality risk from traffic and workplace accidents
Human health – morbidity	PM_{10}, O_3, SO_2	Respiratory hospital admissions
	PM_{10}, O_3	Restricted activity days
	PM_{10}, CO	Congestive heart failure
	Benzene	
	Benzo-[a]-pyrene	Cancer risk (non-fatal)
	1,3-butadiene	
	Diesel particles	
	O_3	Asthma attacks
		Symptom days
	Noise	Myocardial infarction
		Angina pectoris
		Hypertension
		Sleep disturbance
	Accident Risk	risk of injuries from traffic and workplace accidents
Building material	SO_2 Acid deposition	Ageing of galvanized steel, limestone, mortar, sand-stone, paint, rendering, and zinc for utilitarian buildings
	Combustion particles	Soiling of buildings
Crops	NO_x, SO_2	Yield change for wheat, barley, rye, oats, potato, sugar beet
	O_3	Yield change for wheat, barley, rye, oats, potato, rice, tobacco, sunflower seed
	Acid deposition	Increased need for liming
Global warming	CO_2, CH_4, N_20, N, S	World-wide effects on mortality, morbidity, coastal impacts, agriculture, energy demand, and economic impacts due to temperature change and sea level rise
Amenity losses	Noise	Amenity losses due to noise exposure
Ecosystems	Acid deposition, nitrogen deposition	Acidity and eutrophication (avoidance costs for reducing areas where critical loads are exceeded)

Source: European Commission, 2005.

systems cannot be resolved, because the top-down approach usually lacks the spatial and temporal resolution needed to track impacts to specific technologies." To address the damages associated with specific technologies requires the bottom-up approach such as was used in the comprehensive ORNL/RFF (ORNL/RFF, 1992–1998) and ExternE (European Commission, 2005) studies.

Both the ORNL/RFF and ExternE studies employ a bottom-up approach, in which environmental benefits and costs are determined using a pathway analysis that follows the energy-technology pollutant emissions from the source, then tracking dispersion in air, soil, and water and ultimately to health and environmental impacts. Both ORNL/RFF and ExternE used a life-cycle approach to characterize externalities associated with electricity production from a variety of technology options. In order to permit comparisons across multiple technologies, the ORNL/RFF and ExternE characterized externalities in monetized units, that is dollars of damage per kWh. This involved the use of detailed models to predict the dispersion from energy supplying facilities of primary pollutants as well as the atmospheric formation of secondary pollutants, specifically ozone and fine particulate matter (see Table 4.10). The ExternE study also considered transportation systems. More recently, Hill et al. (2009) assessed life-cycle impacts from air emissions attributable to transportation fuels. They used a life-cycle approach to assess the potential impacts of emerging

Box 4.5 | US National Research Council study on the "hidden costs" of energy

In 2008, the US Congress asked the National Research Council (NRC) of the US National Academy of Science to prepare a report that defined and evaluated "key external costs and benefits – related to health, environment, security, and infrastructure – that are associated with the production, distribution, and use of energy but not reflected in market prices or fully addressed by current government policy." The NRC released this report in late 2009 (NRC, 2009b). To assess damages, the committee used a life-cycle approach with relatively high spatial resolution for characterizing emissions and exposures attributable to energy used in the United States by electricity generation, transportation systems, process heat, and building heating/cooling. They applied these methods to a year close to the present (2005) for which data were available, and also to a future year (2030) so as to gauge the impacts of possible changes in technology. In addition to impacts in the near term (health damages), the committee considered damages in the future attributable to emissions of atmospheric greenhouse gases.

The report found that, in 2005, the unpriced impacts of energy supply amounted to US$120 billion. This amount is due mainly to the negative impact of air pollution on health. Of this amount, US$62 billion was attributable to electricity (mainly coal) and about US$56 billion was attributable to transportation, with the remainder due to process heat and comfort control. The long-term damages from climate change were estimated to be comparable (~US$120 billion) and security costs were not quantified. Coal-fired plants, which produce about half of US electricity, had an impact of about US¢3.2 of "nonclimate" damages for every kilowatt-hour (kWh) generated. In contrast, natural gas electricity had an impact of US¢0.16. In the transportation sector, which accounts for 30% of US energy use, the estimated unpriced health damages of US$56 billion works out to US¢0.7–1 per vehicle km traveled. The estimated air pollution damages associated with electricity generation in 2030 will depend on many factors, such as the future mix of generation technologies, end-use efficiency, air pollution regulations, etc. With regard to transportation impacts, the committee noted that substantially reducing nonclimate damages related to transportation by 2030 would require major breakthroughs, such as cost-effective technologies to create cellulosic biofuels and to capture and store carbon from coal-fired power plants. In addition, great increases in renewable or other forms of electricity generation (for electric vehicles) with lower emissions would be needed. Further enhancements in fuel economy will help, especially for emissions from vehicle operations, although they are only about one-third of the total life-cycle emissions (NRC, 2010).

biofuels relative to gasoline. The impact pathways included in ExternE are listed below.

The NRC (2010) report on the unpriced consequences in the United States considered impacts from all forms of energy supply, distribution, and use. The approach and findings of this report are summarized in Box 4.5. Although these results are most relevant to North America, they provide key insights about the relative magnitude of the health and environmental impacts from existing and emerging energy technologies. This report makes clear that, even for relatively clean energy technologies, the upstream inputs can have a significant impact because they often rely on existing technologies for energy inputs. For example, the production of fuels, whether from biomass or from petroleum, requires a significant amount of energy that could be coming from a coal-fired power plant.

4.8.4 Biofuels

Biofuels have become the focus of both governments and industry efforts to find technically feasible and carbon-neutral fuels for transportation and (to a lesser degree) electricity production. The challenge for biofuels is to compete with fossil-based fuels in terms of cost and impact. The enormous world demand for liquid fuels makes it inevitable that a biofuel economy will involve significant changes in agricultural, fuel-production, and transportation infrastructure. Building and operating this infrastructure will involve many complex technical and policy choices. Addressing these complex choices requires research to anticipate the nature and scale of the supply/demand systems that will arise in large-scale deployment of biofuels (Energy Biosciences Institute, 2010). However, the current methods used to measure, evaluate, and regulate human health impacts and benefits of biofuels suffer from a number of information gaps and have not been fully integrated into an LCA framework. Moreover, the call for biofuels gives rise to environmental and ethical questions regarding the impacts in rural communities from deforestation, food price changes, and loss of ecosystem services that can accrue when monoculture crops replace extant systems.

Ethanol derived from corn or sugarcane as an additive to or substitute for gasoline, along with biodiesel derived from vegetable oils or waste animal fat, are currently the largest and most economically viable biofuels options. However, biofuels can be produced from a wide variety of plant materials and wastes. The biofuel feedstocks receiving the most attention include corn stover (stalks and cobs), perennial grasses (switchgrass and miscanthus), sorgum, algae, trees and dedicated woody crops, and even garbage. Because plants absorb CO_2 during growth and may

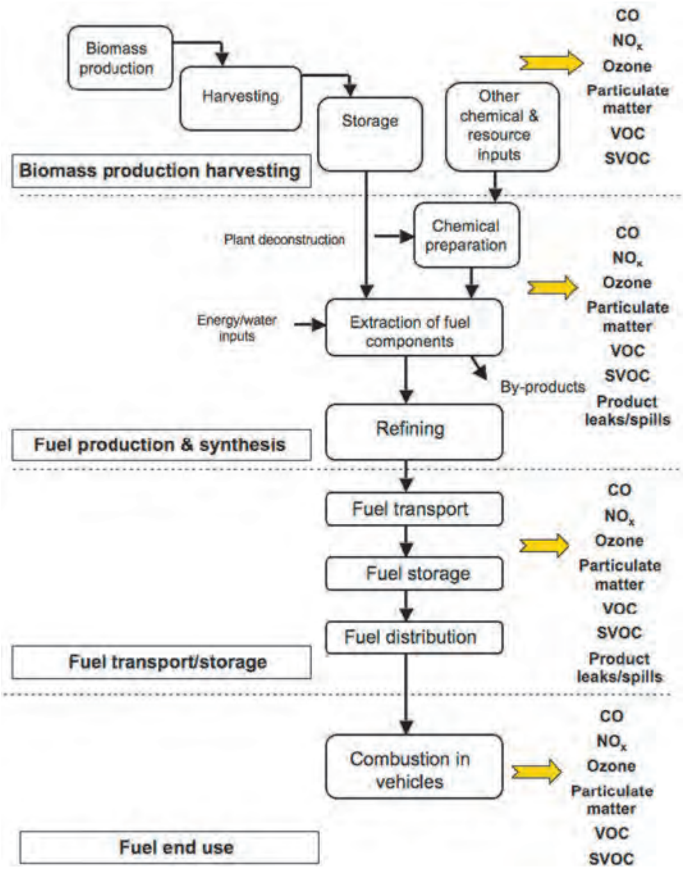

Figure 4.13 | Pollutants associated with biofuel production, transport and use.

increase stores of soil organic carbon (Tilman et al., 2006), biofuels may reduce GHG emissions relative to petroleum-derived fuels. Many studies (see, for example, the review in NRC, 2010) conclude that there are at least small, positive life-cycle GHG benefits from most biofuels. But there continues to be debate concerning the net GHG effects from first-generation biofuels, particularly corn-based ethanol.

In addition to potential reductions in GHG emissions, vehicle tailpipe emissions of many air pollutants harmful to human health will be different and may be lower with biofuels (McCormick, 2007). Questions remain regarding how shifts from petroleum-based fuels to biofuels will affect the combustion-phase emissions of air pollutants. Evidence for lower primary particle emissions must be weighed against evidence for potentially higher VOC emissions, which could increase ozone and secondary particle formation. Whether and how much biofuels reduce human health impacts (see Figure 4.13) relative to fossil fuels depends strongly on how they are produced, distributed, and combusted (Robertson et al., 2008). Energy inputs, fertilizer use, biomass yields, conversion efficiencies, pollution control technologies, and direct and indirect damages to water supplies and land all determine the cumulative impacts on human health from both biofuels and fossil fuels (Hill et al., 2006; Fargione et al., 2008; Searchinger et al., 2008).

In characterizing the life-cycle health impacts associated with liquid transportation fuels from biomass, one needs to consider the emissions generated at each of the following stages (see Figure 4.14):

- production of the feedstock (farm or forest externalities);
- transportation of the feedstock to the processing facility;
- processing of the feedstock into liquid fuels;
- transportation of the fuel to distribution endpoints; and
- downstream effects of using the fuel.

The last two steps are identical to any liquid transportation fuel and, at least for air emissions, have been addressed by air quality studies and models. But these studies have significant uncertainties, so it remains difficult to make an accurate characterization of the overall disease burden from gasoline, much less to project future scenarios. The upstream impacts of biomass feedstock effects will be quite location specific, as different feedstocks will be economically viable in different locations (e.g., corn stover and switchgrass in the corn belt, miscanthus in warmer climates, trees and forestry in the southeast, etc.). In addition, the health impacts associated with any given feedstock are also likely to vary by specific field/watershed within a region (depending on climate, land use history, soils, slope of the land, proximity to water bodies, etc.) and can be attenuated by farming practices (use of conservation tillage, nutrient management of both fertilizer and manure applications, placement of buffers or wetlands, etc.). Finally, transportation of feedstocks to processing facilities is expected to remain expensive, even after technological improvements, so that numerous, small processing facilities located throughout the landscape is a likely configuration of the industry. This means that health impacts associated with production and transportation of the feedstock and liquid fuels will be both site-specific and widespread.

Hill et al. (2009) estimated that for "each billion ethanol-equivalent gallons of fuel produced and combusted in the USA, the combined climate-change and health costs are US$469 million for gasoline, US$472–952 million for corn ethanol depending on biorefinery heat source (natural gas, corn stover, or coal) and technology, but only US$123–208 million for cellulosic ethanol depending on feedstock (prairie biomass, miscanthus, corn stover, or switchgrass)." However, their analysis does not distinguish mortality from morbidity or define the equivalent disease burden associated with these numbers. Moreover, their approach focuses on air emissions and excludes the impacts of toxic air pollutants and releases to soil and water. Future life-cycle assessments are needed to address a full range of air emissions, as well as emissions to surface water, soil, and groundwater, which have complex and significant pathways from release to human intake (e.g., food pathways).

The debate concerning the net GHG effects of biofuels centers on indirect land use changes. Indirect land use refers to crop allocation changes occurring indirectly as a result of biofuels policies and the effect of such

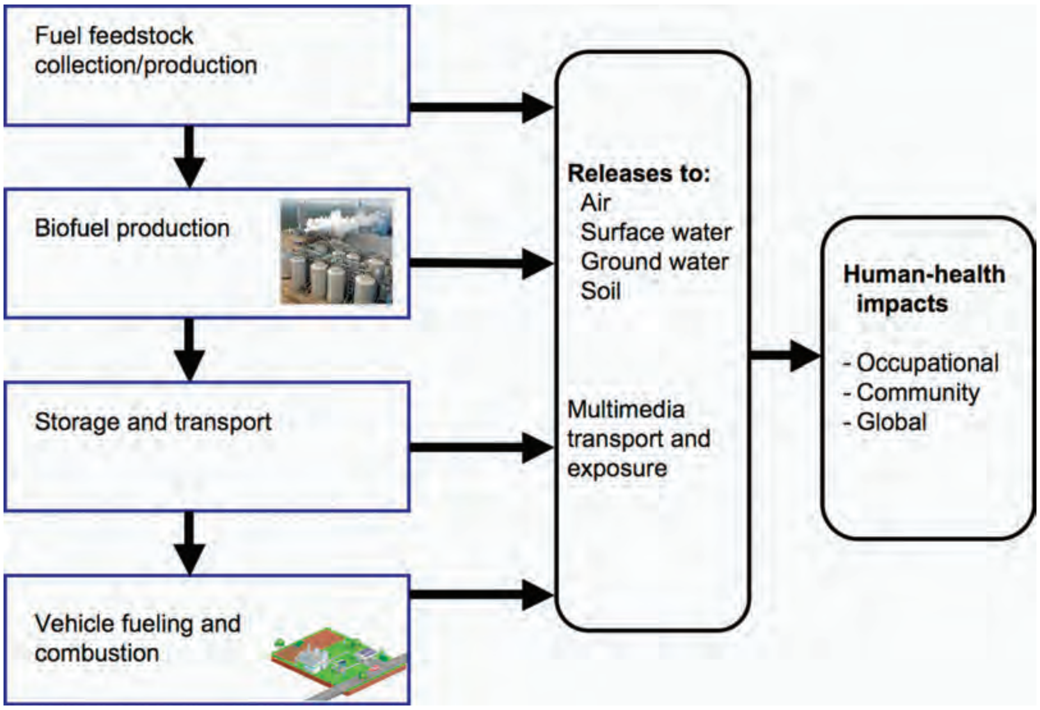

Figure 4.14 | An illustration of the life-cycle approach showing the link of human health impacts to the major life stages of biofuel production and use.

changes on GHG emissions. It has been a major source of discussion since Searchinger et al. (2008) published a paper that explains how increasing demand for corn or farmland causes crop prices to increase, making it profitable for farmers to increase their acreage. If this increased acreage comes from plowing up land that has not been in agricultural production and/or is particularly environmental sensitive (e.g., rainforests in Brazil, pristine ecosystems in the United States), this could actually increase CAP emissions (since burning rainforests would release lots of carbon) and have other detrimental environmental concerns. There is continuing study of this issue. A recent report by the US Environmental Protection Agency considered a range of biomass production scenarios and found significant variability with regard to indirect land use (US EPA, 2009). In some cases, their analysis suggests that significant reduction in CAP emissions relative to gasoline could be largely offset by indirect land use changes. In other cases, the effect is small. These types of results focus attention on a formal treatment of uncertainties in the life-cycle assessment.

4.8.5 Synfuels

Synfuels are considered emerging technologies because most synthetic fuels technologies are either not yet cost-competitive with existing fossil fuels or because they are still in a research and development phase. Synthetic fuels can be made from coal, oil shale, or tar sands. Various fuel gases, such as substitute natural gas and synthesis gas (made from CO and hydrogen) are also included in this category. Synthetic crude oil (often called "syncrude") is a complex mixture of hydrocarbons somewhat similar to petroleum. It is obtained from coal (liquefaction), from synthesis gas (a mixture of carbon monoxide and hydrogen), or from oil shale and tar sands. Gaseous fuels can be produced from sources other than petroleum and natural gas. Syncrude mixtures have a number of key differences in composition relative to petroleum. For example, syncrude from coal usually contains more aromatic hydrocarbons than petroleum. The most important current source of synthetic crude oil is the tar sand deposit that occurs in northeastern Alberta, Canada. Tar sand is a common term for oil-impregnated sediments that can be found in almost every continent. The routes by which synthetic fuels can be prepared from coal involve either gasification or liquefaction.

Atmospheric emissions from synfuel production are generated from mining, processing, retorting, and waste disposal. Large emissions of PM can arise from mining, blasting, conveying, crushing, and on-site retorting operations. The on-site liquefaction/gasification needed to mobilize synfuels also poses the potential for large emissions of oxides of sulfur and nitrogen, mercury and other metals, and carbon monoxide, as well as large numbers of organic compounds, including alkanes, benzene, and polycyclic aromatic hydrocarbons (PAHs) to the local airsheds.

Production of synthetic fuels from geological formations such as oil sands or oil shale also have the potential for impacting human health through significant reductions in water quality. The impacts on water quality are both direct and indirect. Direct impacts arise from the release of contaminants to surface and groundwater from both routine and off-normal operations. Synthetic fuel operations produce large amounts of wastewater that must be stored, treated, and moved through pipelines. Even under ideal conditions, the treatment process can introduce trace amounts of metals and toxic organic compounds to surface and groundwater. Moreover, off-normal events such as leaks in pipes and containment ponds, which can be frequent, will add even more of these substances to both surface and groundwater. Indirect effects are those associated with large demands on limited water supply and impacts from disrupting water-bearing formations. For example, extracting one barrel of oil from an oil sand requires many barrels of water. The demand on surface and/or groundwater for synfuel mining and processing will limit the amount of water available for diluting the pollutants from these processes. Lack of available fresh surface or groundwater can be a disease burden in and of itself. The alteration of geologic formations due to mining operations can limit the storage and transmission of both surface and groundwater, leading to a reduction of freshwater and the health consequences of this privation.

Significant human health impacts are associated with the production and use of synfuels (NRC, 2010). These technologies have documented impacts on occupational health as well as the health of local, regional, and global populations. The life-cycle impacts of synfuels include both upstream processes for extraction, transportation, and reefing the fuel-use stage. The upstream stages have potentially significant local and even regional impacts on air, surface water, and groundwater with resulting impacts on human health. In particular, the need to liquefy or gasify the fuels from the formations that supply them will result in CAP emissions that impose both local and global disease burdens. In the refining and combustion process, the impacts of synfuels are likely to exceed those of an energy-equivalent quantity of gasoline; however, there are currently insufficient data available to accurately make this assessment (NRC, 2010).

4.8.6 Large-Scale Solar and Wind Power Systems

Solar energy has been deployed in both small-scale (mainly rooftop) applications and in large-scale electrical production. A number of large-scale solar power plants are already in operation worldwide, with plans slated for others. Three large-scale technologies transform solar radiation into a form that provides electricity: photovoltaic cells, which generate electricity directly; concentrating solar power thermal systems, which use an absorption medium such as water or oil to transfer absorbed heat to a steam generator that drives a turbine; and solar towers, which are effectively chimneys where rising hot air powers turbine generators.

Wind power or wind energy is the process by which the wind is used to generate mechanical power or electricity and is one of the fastest-growing forms of electricity generation in the world. Archer and Jacobson (2007) produced a global wind-energy resource map that estimated the global potential for wind-generated energy at 72 terawatts, 40 times the worldwide demand in 2000.

Large-scale solar and wind systems are not free of health and environmental impacts. Issues of water demand, land use, maintenance, materials inputs, and energy storage raise concerns for environmental, occupational, and community health impacts. Interest is growing in the large-scale use of nanomaterials in solar applications. Energy storage is an issue currently being addressed with new technologies that may require large quantities of materials whose toxic properties are not well studied. Constructing new transmission lines to areas with the best wind and solar resources also poses significant environmental problems. There is no indication, however, that the overall health burden of these systems will be even close to those from traditional fossil fuel systems. Moreover, the health burdens for large wind power and solar power systems are likely to be lower than even advanced fossil and nuclear power systems. Nevertheless, it is important to anticipate risks in advance in order to head off any unpleasant surprises as new systems come into widespread use.

4.8.7 Geo-engineering Schemes

Concerns about the environmental impacts of GHG emissions and the persistent pollutants from energy technologies have led to a call for large-scale "geo-engineering" projects for mitigating the impacts of global pollutants. Geo-engineering is the deliberate modification of Earth's environment on a large scale to provide for human needs and promote habitability. Keith (2001) emphasizes that it is the deliberateness that distinguishes geo-engineering from other large-scale, human impacts on the global environment, such as those that result from large-scale agriculture, global forestry activities, or fossil fuel combustion. Originally, the term geo-engineering referred to a proposal to collect CO_2 at power plants and inject it into deep ocean waters. The concept of geo-engineering now also includes:

- underground storage of CO_2;
- fertilization of oceans with urea, a nitrogen-rich substance, or with iron, a limiting nutrient, to encourage growth of plankton;
- deflection of sunlight from the Earth through the use of a giant space mirrors;
- injection of sulfur particles into the stratosphere in order to modify the Earth's albedo;

- cloud-seeding by spraying seawater in the atmosphere to increase the reflectiveness of clouds; and
- windscrubbers to filter carbon dioxide from the air.

Each of these concepts carries with it some risk of health and environmental impacts that have not been fully identified or evaluated. In addition, most of these concepts are energy intensive and will thus have an impact that depends on the quantity of energy required and the source of that energy.

4.8.8 Advanced Materials in Energy Systems

Advanced materials such as nanotechnology materials and advanced semiconductor technology play a growing role in both energy supply and energy use. Nanotechnology is increasingly impacting the US and world energy balance, on both the supply and demand sides. On the supply side, nanotechnology is being used to optimize supply from existing energy sources (e.g., crude petroleum) and to exploit new sources, such as heavy oil, liquefied coal, and solar energy (including using solar energy to produce hydrogen). Nanotechnology is also improving and opening new possibilities for the transmission and storage of energy, especially electricity and possibly hydrogen in the future. On the demand side, nanotechnologies have the potential to reduce energy use by making it possible to manufacture lighter and/or more energy-efficient automobiles and appliances. Nanotechnologies can also be used to improve energy efficiency in buildings.

The health and environmental impacts of advanced materials such as nanotechnology materials are not well characterized. There are a number of concerns about both occupation and environmental exposures to the widespread use of these materials and what impact that will have on disease burden (NRC, 2009a).

4.9 Energy Efficiency

4.9.1 Key Messages

- Increases in combustion efficiency have the potential to greatly improve human health, especially in households that use solid fuels for cooking.
- Measures to increase energy efficiency in buildings can improve health by reducing cold-related morbidity and mortality and by increasing psychosocial well-being.
- In homes with relatively low levels of air exchange, energy efficiency measures can have some negative impacts on health by increasing exposure to dust, mold, radon, volatile organic compounds, and indoor tobacco smoke.
- Energy efficiency projects require capital. Fuel taxes or tariffs may be levied to account for these expenditures, while subsidies for poorer consumers may be needed to counteract the effect of increased fuel prices.

4.9.2 Energy Efficiency, Energy Use, and Health

Energy efficiency is often looked upon as the most desirable approach to limiting energy use and as potentially the most cost-effective means of achieving net health benefits. Obtaining the same level of energy service with less primary energy input should entail lower fuel cycle risks, reduce atmospheric emissions of pollutants, limit demands on infrastructure, lower costs, and contribute to economic competitiveness. Although all these factors are generally true, the relationship between energy efficiency and health is more complex.

To a large degree, in fossil fuel combustion, efficiency equates with cleanliness of burning and hence with lower emissions of health-damaging pollutants for a given quantity of fuel and a specified level of energy service. This has most immediate and direct relevance to the indoor combustion of biomass for cooking and heating in low-income households (see Section 4.2), where efficiency of stove technology may appreciably influence exposure to indoor air pollutants, especially for women and children.

Some argue that, at a societal level, increasing efficiency (and hence improving the affordability of energy services) can promote greater overall use of the technology in question than otherwise would occur, resulting in a rise in total per capita energy use, and potentially greater community-level pollutant emissions (Smil, 2005). Among poor populations, an increase in energy services due to greater energy efficiency can have major welfare benefits, including better health. This set of issues is sometimes called the "takeback" or "rebound" effect and is discussed in more detail in Chapter 10.

Increased energy efficiency is a factor in the web of socio-technological influences that contribute to (industrialized) patterns of supply and demand, which have many detrimental (as well as beneficial) consequences for health in rich countries. Among the risks are those associated with increasing dependence on motorized transport (in relation to risk of road injuries and deaths; physical activity with its consequences for obesity, diabetes, cancer risks; and many other health effects; as well as adverse effects on the quality of urban living); overconsumption of energy-dense, processed foods high in salt and saturated fats, derived from intensive agriculture; and diets with a high proportion of meat and dairy products.

Energy efficiency is seen as one means of helping to limit the vulnerability to price volatility in global energy markets and of establishing greater energy security – an argument that applies at national and household levels (see Chapter 5). Though opinion about the imminence and consequences of peak oil remains divided (Deffeyes, 2001; Frumkin et al., 2007), there is no doubt that the world's low-cost energy reserves are being steadily depleted. Over time, the costs of extraction will rise in financial, environmental, and energy terms, as deposits become less and less accessible. There are justifiable concerns that this trend will be a driver for economic change and restructuring in many countries, with adverse effects on health and life expectancy. Reducing energy dependence through greater efficiency may help to limit these adverse impacts.

Among the various methods by which energy efficiency may be improved is the use of more distributed energy supply systems based on microgeneration and combined heat and power systems. Though broadly desirable, significant uncertainties remain about the adverse impacts that multiple microgeneration facilities may have on air quality in some settings, relative to centralized energy supply and distribution systems. This is due in part to the higher intake fraction (see Box 4.1) of the emissions from such facilities.

Increasingly, energy efficiency interventions – including programs of home insulation and heating system upgrades, as well as building regulation – are being used to tackle GHG emissions. While such interventions are likely to be broadly beneficial for health (e.g., resulting in warmer indoor temperatures in winter, lower fuel use/cost, improved use of space with various psychosocial benefits, etc.), there can be important unintended consequences. One method to increase energy efficiency is to limit the degree of uncontrolled ventilation by improving the air tightness of windows, doors, and other parts of the building fabric. While this may have little effect if the relative reduction in ventilation is small, it may have more critical impact in dwellings that already have fairly modest ventilation rates. The potential adverse health consequences include hazards relating to dampness and mold, indoor air quality (especially increases in radon levels), and in some circumstances, risk of adverse heat-related effects.

There is limited epidemiological evidence about many of these connections, which often are modified by local circumstances. The impacts of energy efficiency therefore cannot be quantified with any precision, despite their importance to a range of energy-related policy decisions.

4.9.3 Household Energy Efficiency

Household energy efficiency merits particular discussion because it is increasingly becoming a target for energy policy in the context of climate change (Stern, 2007; Friedlingstein, 2008) and recent fuel price rises. In developed countries, it is commonly being addressed through a combination of building regulation (e.g., minimum energy efficiency standards for new dwellings) and initiatives aimed at the refurbishment/upgrading of the much larger pool of existing housing stock. The scope and cost-effectiveness of energy efficiency gains is generally greatest for new dwellings, where efficiency measures can be incorporated at the design stage. However, in nearly all settings, new dwellings account for a tiny fraction of the overall housing stock, so that in the short term, the larger potential for changing collective energy efficiency arises in relation to the upgrading and retrofitting of existing dwellings. For such dwellings, the types of upgrades may be limited (older housing stock may not have cavity walls, for example), the basic building fabric may be inherently inefficient from a thermal perspective, and the health benefits and financial returns are correspondingly lower.

The cost and benefits of specific building standards and efficiency upgrades depend on numerous factors, including, crucially, fuel type and price. It is also a function of occupancy levels and occupant behaviors. To date, few systematic attempts have been made to assess the associated costs and benefits to health, though such assessments are now beginning based on risk assessments of a range of housing-related hazards. Energy efficiency upgrades have a number of (mainly unquantified) adverse health costs as well as benefits.

4.9.4 Potential Adverse Health Effects

The main concerns about adverse health effects arise from reduced air exchange, which may increase indoor pollutants. In the most air-tight dwellings, these problems can be alleviated by mechanical ventilation and heat recovery (MVHR) systems, which allow greater ventilation while maintaining energy efficiency by recovering heat from the vented air. However, because MVHR systems require high levels of air tightness for effective operation, it is critical that they are correctly installed and maintained. In dwellings reliant on passive ventilation, pollutants derived from indoor or 'under-house' sources tend to rise as air exchange is reduced.

4.9.4.1 Radon

Radon has received surprisingly little attention despite strong theoretical arguments about its detrimental health effects if ventilation rates are lowered. Radon is a naturally occurring, colorless, odorless radioactive inert gas, with a half-life of 3.8 days, formed from the decay of radium. It is a significant contaminant of indoor air worldwide. Radon results from radioactive decay in rock formations beneath buildings or in certain building materials themselves. As a very heavy gas, it tends to accumulate at floor level.

Exposure to radon increases the risk of lung cancer (NRC, 1999; Darby et al., 2005). A common action level for remediation is 200 becquerels per m^3, a level that corresponds to a 3% lifetime excess risk of lung cancer. In many countries, it is the second most important cause of lung cancer deaths after cigarette smoking, accounting for around 10% of all lung cancer cases in the United Kingdom, for example.

Reduction in air exchange because of energy efficiency may give rise to an appreciable shift in the distribution of indoor concentrations, and hence alter risks of lung cancer. A variety of cost-effective engineering solutions are available to deal with high radon levels. The concern is that dwellings with elevated levels of radon may go unrecognized, or the energy efficiency interventions give rise to a more subtle shift in the population average exposure.

4.9.4.2 Dampness/Mold and House Dust Mite

Dampness and mold are primarily determined by indoor (relative) humidity. With energy efficiency, there is a tradeoff between higher temperatures (which tend to lower humidity, especially in winter months, and thus to decrease mold risk) and lower ventilation, which tends to increase humidity (Oreszczyn et al., 2006).

Although there is insufficient evidence, as yet, of a causal link between the presence of visible mold and the many putative health effects, several epidemiological studies show associations between visible mold (≥ 1 m^2) and respiratory and other symptoms, including asthma, rhinitis, cough, wheeze, nausea, vomiting, and general ill health (Bornehag et al., 2004; Davies et al., 2004). The most vulnerable groups are young children, the elderly, allergy sufferers, and immuno-compromised individuals.

It is difficult to generalize about the patterns of ventilation and mold, which depend on climatic factors, quality of housing stock, and multiple other factors, but mold is a common problem in most settings. At reasonably high levels of air exchange (> one per hour), temperature improvements associated with energy efficiency may tend to lower mold risks. However, concerns arise towards the low end of air exchange in developed countries, i.e., less than 0.5 per hour.

4.9.4.3 Other Indoor Pollutants

Lower ventilation rates may also be important for a range of other pollutants arising from indoor sources (COMEAP, 2004).

- *Volatile Organic Compounds (VOCs)* include over 200 component chemicals typically existing in indoor air, including formaldehyde, benzene, and benzo(a)pyrene (BaP). Potential health effects are complicated: biological effects vary according to the specific chemical components present in the mixture, as well as with environmental factors such as temperature and humidity. Indoor sources are varied and include foam insulation (urea formaldehyde foam insulation), particle board used for construction, furniture, furnishings, and household cleaning agents. Indoor levels in developed countries are generally approximately 10-fold higher than ambient levels. Increased concentrations tend to be associated with newer and/or recently decorated houses. Health effects are poorly characterized but principally relate to allergic responses (Mendell, 2007), comfort and well-being, and some (theoretical) genotoxic/carcinogenic risk.

- *Products associated with combustion, especially nitrogen dioxide (NO_2) and particles* are a significant component of indoor air pollution. The major source of indoor NO_2 is from cooking with gas. On average, concentrations encountered indoors are not high enough to produce serious acute effects but are thought to be sufficient to cause a reduction in lung function and an increase in response to allergens that can cause narrowing of the airways in some sensitive individuals. Other possible health effects of indoor NO_2 include: increased likelihood of respiratory infection, symptoms, or illness in children living in homes using gas for cooking and heating; reduction in lung function in women living in homes using gas for cooking and heating (de Bilderling et al., 2005); impaired respiratory health associated with long-term exposure to NO_2; and a possible effect of NO_2 on the response to allergens in specifically sensitized individuals. Recent work by Chauhan et al. (2003) has shown that exposure to nitrogen dioxide increases the likelihood of viral infections in children and increases the bronchoconstrictor response seen in asthmatic subjects so infected (COMEAP, 2004). This is an important finding, as it is known that such infections play an important role in triggering attacks of wheezing in young children.

- *Carbon monoxide* is an under-recognized risk associated with poorly ventilated or maintained boilers and burners. In relation to energy efficiency, the main impact is more likely to be *reduced* likelihood of exposure (from more modern and efficient combustion devices installed as part of energy efficiency upgrades) than higher levels of exposure from reduced air exchange.

- *Tobacco smoke* poses a significant risk in households where one or more family members are smokers. In dwellings with lower air exchange rates, the known adverse effects of environmental tobacco smoke may be greater for children or other family members.[17]

4.9.4.4 Heat Risks

Greater energy efficiency has the potential to improve protection against heat-related risks by buffering against peak temperatures and smoothing out the diurnal fluctuations in indoor temperatures during heat waves. However, energy efficiency may be detrimental where solar gain is high (e.g., dwellings with large areas of glass facing the sun), as the high level of insulation in the building fabric may then act to maintain and accentuate high indoor temperatures. This may be a particular problem with high energy efficiency, low thermal mass dwellings. Traditional

17 Risks from secondhand tobacco smoke exposures are quantified in the latest CRA. For further information, see Footnote 1.

Table 4.11 | Effects of cold temperature on cardiovascular mortality, and modification by standardized indoor temperature.

Quintile of standardized indoor temperature. Range (mean) in degrees celsius	No. of deaths	% increment (95% CI) in mortality per degree celsius fall in outdoor temperature	
		Unadjusted	Adjusted for region
CARDIO-VASCULAR			
1 <14.8 (13.3)	2648	1.7 (0.5, 2.9)	2.2 (0.6, 3.9)
2 14.8- (15.7)	2555	1.1 (-0.1, 2.3)	1.1 (-0.5, 2.8)
3 16.6- (17.2)	2314	1.2 (-0.0, 2.4)	1.2 (-0.5, 2.9)
4 18.4- (18.7)	2523	1.4 (0.2, 2.6)	1.3 (-0.4, 3.0)
5 19.4- 27.0 (21.0)	2963	0.2 (-1.0, 1.3)	-0.1 (-1.7, 1.5)
Trend (change per degree celcius increase in hall temperature)		-0.15% (-0.28, -0.03)	-0.13% (-0.26, -0.00)

Source: Wilkinson et al., 2009.

dwellings in hotter climates typically have high thermal mass, small solar gain (small outward facing windows and doors, inner courtyards), and orientations to promote natural ventilation at night. Although there is reasonable understanding of how dwellings can be adapted to heat, countries that currently do not have hot climates may be optimized for cold rather than the hotter summer conditions that may prevail under climate change.

4.9.5 Health Benefits

Despite the list of potential adverse consequences, improvements in energy efficiency are likely to lead to net benefits through various routes, at least in communities where there are appreciable cold-related impacts and high energy costs.

4.9.5.1 Reduced Cold-Related Morbidity and Mortality

Burdens of cold-related mortality and morbidity are substantial in most temperate climates and are measurable in almost all populations studied to date (see, for example, McMichael et al., 2008). Much uncertainty remains about the degree to which housing quality affects this vulnerability, but evidence from the United Kingdom, which has a comparatively large burden of winter excess death, provides the most relevant quantification (Wilkinson et al., 2001), broadly consistent with other published work (The Eurowinter Group, 1997; WHO, 2007). It shows that the magnitude of cold- and winter-related excess death is greater in people living in dwellings that have low winter indoor temperatures. Specifically, there is evidence to quantify the risk of cold-related mortality in relation to adequacy of home heating, as reflected by the standardized indoor temperature – the indoor temperature measured when the outdoor temperature is 5ºC (Table 4.11). There is less evidence regarding the relationship between housing characteristics and health impacts other than mortality.

4.9.5.2 Psychosocial and Mental Health Benefits of Warmer Indoor Environments

A growing body of evidence indicates that improved household energy efficiency is accompanied by important changes in the use of space, social interaction, and related psychosocial well-being (Gilbertson et al., 2006). What is less clear is the contribution of different effects: sense of control, reduced costs of home heating (for low-income families), or effects that are a direct function of warmer indoor environments.

4.9.5.3 Indirect Effects on Environmental Pollution and Climate Active Pollutant Emissions

Although household energy efficiency is likely to have its greatest impact on health through direct effects on householders, the impact on wider environmental emissions of toxic pollutants and CAPs is also important. However, the evidence is mixed whether energy efficiency gains translate into lower emissions of CAPs. To date, the evidence suggests that much of the benefit of energy efficiency is taken as higher indoor temperatures in winter rather than as energy savings.

4.9.6 Conclusion

The goal of reducing CAP emissions should assume should central importance in the energy policies of many national and local administrations. A range of policy instruments and interventions are could be used to try to limit energy use and drive energy efficiency, as well as to support a modal shift towards renewable energy sources. However, most energy efficiency improvements require appreciable capital investment, and renewable energy sources currently remain more expensive than conventional (fossil) fuels. Carbon taxes or tariffs to support market shifts therefore generally act to increase fuel prices. This may be damaging to poor groups in higher-income countries already unable to pay for their fuel or to those in developing countries if households are driven down the "energy ladder" to polluting biomass fuels by higher fuel prices. To avoid the adverse health consequences of such policies, it is necessary to provide direct support to low income groups through price subsidies ("winter fuel payments" and the like), though this in part negates the rationale for the carbon tax, or to combine carbon taxation with targeted infrastructure investment to improve energy efficiency for disadvantaged groups.

From a health perspective, however, it is not always clear that such investments represent the most cost-effective gains in public health, as when they are set, for example, against other potential forms of health care expenditure. A consequence of the imperative of tackling the challenges of climate change is that substantial resources will need to be transferred from richer to poorer populations to assist them in attaining and using efficient, low-carbon technology.

4.10 Co-benefits for Climate Change Mitigation and Health Promotion

4.10.1 Key Messages

- For long-term climate protection, CO_2 emissions need to be reduced through energy efficiency and shifts away from fossil fuels, both of which may reduce health-damaging pollutants even if no special emission controls are used.

- Reducing most CAPs, which have substantial direct and indirect health impacts, will lead to substantial health and climate protection over the next decades.

- Other important co-benefits opportunities for health and climate include providing access to reproductive services for women, working to lower meat consumption, and actions to redesign cities and transport systems to reduce physical inactivity.

- Reduction of the CAPs, nitrogen and sulfur emissions, although important for health and ecosystem protection, unfortunately slightly aggravates global warming by reducing the cooling effects of the light-colored particles that are created from current emissions.

There are a number of potential co-benefits opportunities, which ameliorate both health and climate, in the wake of changes in the world's energy system to reduce CAPs.[18] For example, reducing fossil fuel combustion in power production will improve air quality (Markandya et al., 2009), preventing respiratory and cardiovascular disease; and an increase in use of mass transit, cycling, and walking will increase physical activity, reduce obesity, and stimulate social contacts (Woodcock et al., 2009). In high-income countries, where average daily intake of red meat typically exceeds nutritional needs, a reduction in meat production and consumption – especially from ruminant animals, including cattle, sheep, and goats – would confer several health and environmental gains, partly through reduction in energy use from processing, storage, and transport (Friel et al., 2009). Another major set of co-benefits can accrue by promoting reproductive rights for women around the world. Studies show that giving women control over their fertility will lower both maternal and child mortality, which are both important parts of the unfinished health agenda worldwide, as targeted in the MDGs (Smith and Balakrishnan, 2009). Helping countries reach replacement fertility earlier than would otherwise occur will, in turn, reduce energy use and climate impacts (O'Neill et al., 2010). Finally, nearly any improvement in energy efficiency or shift to different sources that reduces carbonaceous fuel combustion will generally have commensurate health advantages, although care must be exercised that other risks are not substituted, for example, from increased indoor air pollution when building insulation is enhanced (Wilkinson et al., 2009).

Although there are a number of examples of important co-benefits to be gained within these classes of interventions, designing acceptable policies to take advantage of them will require consideration of other factors, among which cost is probably most important. It is not straightforward, however, to convert either health or climate protection benefits into economic terms, let alone in a consistent way across both classes of benefits, in order to determine which projects should be undertaken first. There is no space in GEA to provide such analyses across the large range of alternative projects, countries, and impacts, but we have provided some entry into the literature in Boxes 4.2 and 4.6.

Not all CAPs are created equal from either a climate or a health standpoint. Some are substantially more damaging than others and, in the case of climate impacts, some actually have beneficial (cooling) characteristics, although all are damaging to health. This creates a complex landscape for planning interventions that have benefits for both health and climate.

To inform this strategy, in Box 4.2 we provide a brief primer of the climate and health characteristics of the major shorter-lived CAPs emitted from the energy sector, all of which have implications for health.[19] Figure 4.15 summarizes what is understood about them at present (Smith et al., 2009). Figure 4.7, which is taken directly from the IPCC Fourth Assessment (Forster and Ramaswamy, 2007), shows the estimated contributions from these agents of global warming in the year 2005 due to all human emissions since 1750. The CAPs are compared by radiative forcing (RF), which is the metric used for the comparisons of the strength of different human and natural agents in causing climate change (Smith et al., 2009).

18 See the special series on co-benefits in the *Lancet* published November 2009, in particular the summary policy paper (Haines et al., 2009).

19 Not discussed are CAPs such as N_2O, H_2, and NH_3, for which fuel combustion is a minor contributor.

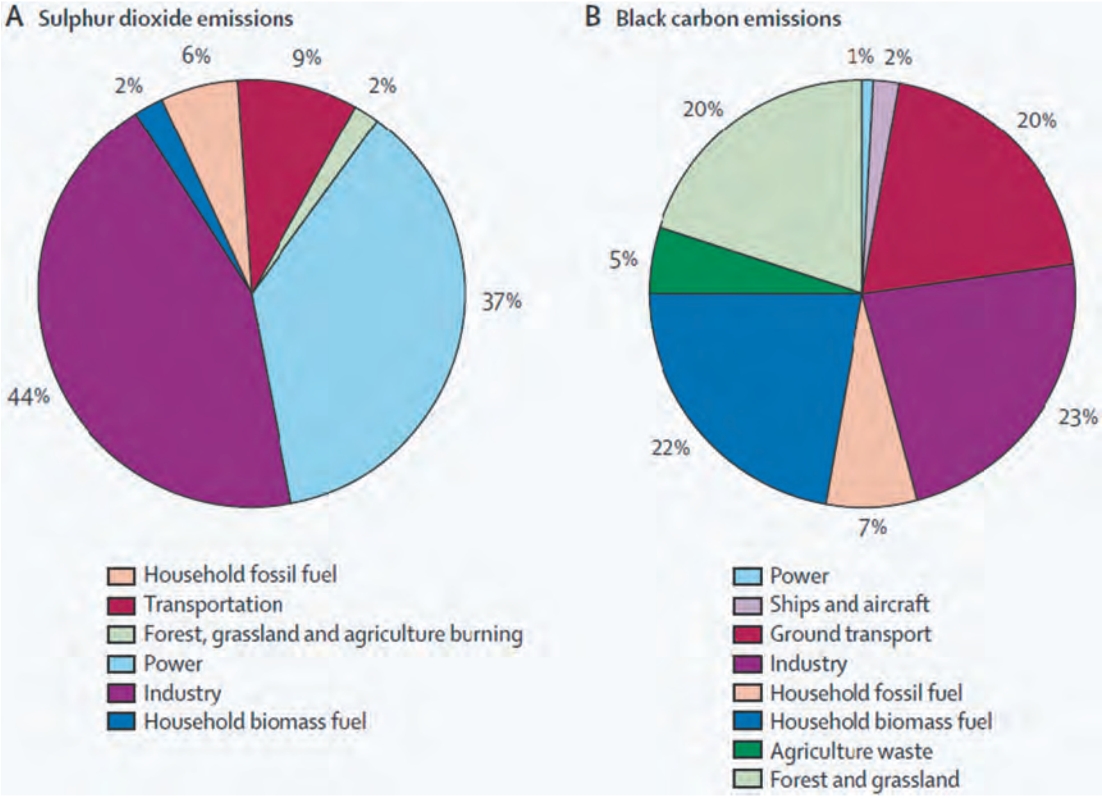

Figure 4.15 | Sulfur dioxide and black carbon emission sources. Source: Smith et al., 2009.

Box 4.6 | Economic evaluations of co-benefits

There is a growing literature attempting to quantify the economic implications of CAP reductions for health and climate protection. Progress has been made in establishing scoping methods (Smith and Haigler, 2008). There are also important and often not well understood atmospheric interactions that require detailed local information and modeling for estimating co-benefits. Nevertheless, studies of growing sophistication, using local data, have been done in Asia and elsewhere to pin down the potentials.[20]

As an illustration of one approach, Figure 4.16 below from Smith and Haigler (2008) compares the cost-effectiveness of a range of interventions in terms of both climate and health protection. For metrics, it uses international US dollars per tonne CO_2-equivalent, which applies a global warming potential to tonnes of methane and nitrous oxides reduced to be able to add them to the tonnes of CO_2 reduced. For health, it uses the approach recommended by the World Health Organization (WHO) for cost-effectiveness, i.e., international US dollars per saved DALY (Murray et al., 2000). WHO recommends that any intervention costing less than three times the local GDP per capita be considered seriously for implementation (WHO, 2003). The price of CO_2-equivalents in early 2012 on the international market was about US$ 9 per tonne CO_2-eq (Carbon Positive, 2012). The projects shown in the figure are only illustrative examples from the literature and are not meant to be best or worst options. Rather, the Figure illustrates one approach for such analysis (see article for details).

20 A good example is the set of studies done in cities around the world as part of the Integrated Environmental Strategies Project of the USA EPA (en.openei.org/wiki/EPA-Integrated_Environmental_Strategies). Many other references are found in Smith and Haigler (2008).

In general, household fuel interventions in poor countries have the highest returns because of the inefficiency by which traditional fuels are currently used, leading to high health-damaging CAP emissions, and the high intake fractions, leading to large health effects.

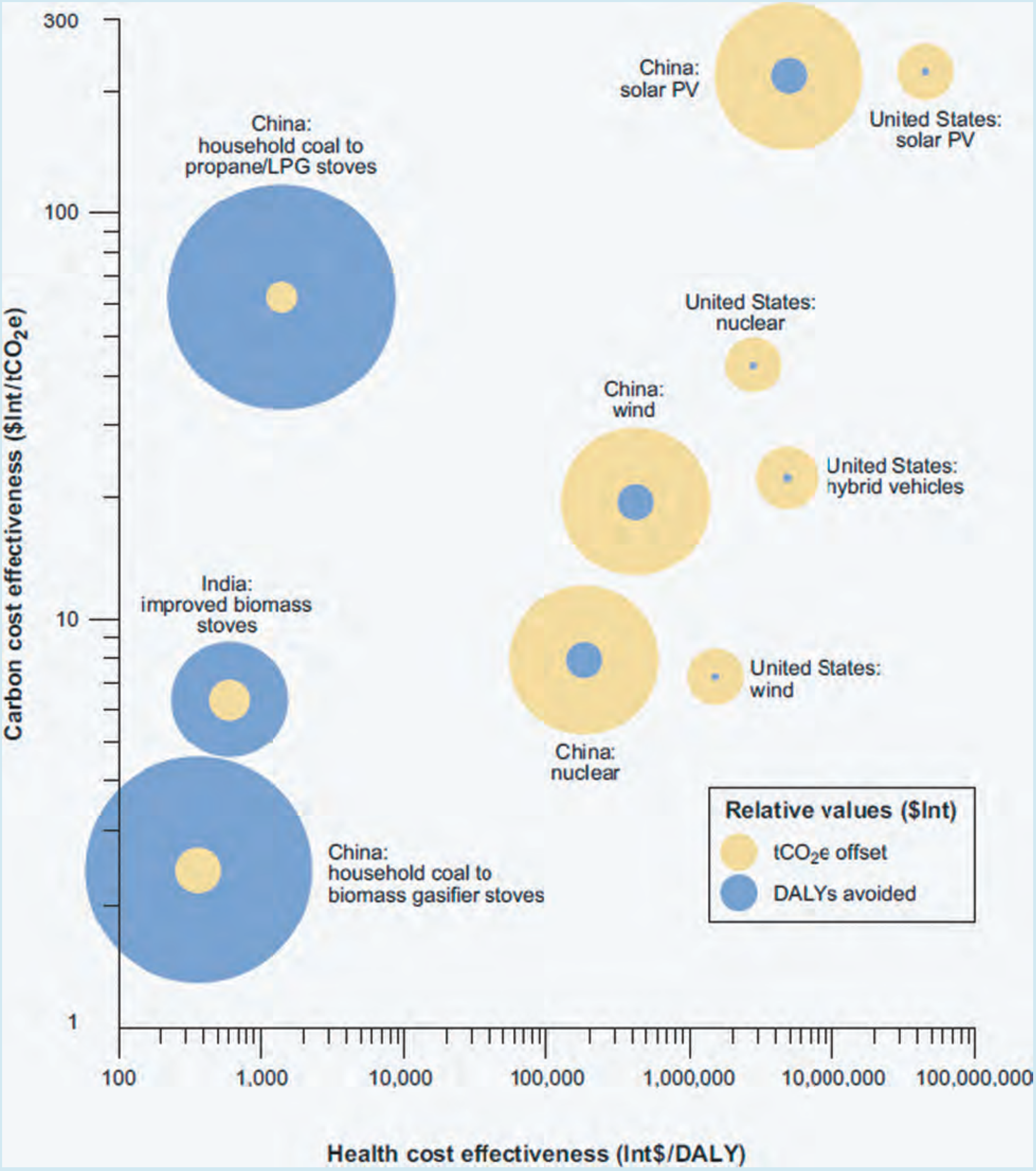

Figure 4.16 | Illustrative examples of co-benefits analysis: comparison of the health and climate cost-effectiveness of household, transport, and power sector interventions. Source: Smith and Haigler, 2008.

Aerosols influence RF directly through the reflection and absorption of solar and infrared radiation (Smith et al., 2009). Some aerosols, such as BC, cause a positive RF (i.e., climate warming) whereas others, such as sulfates, cause a negative RF (i.e., climate cooling) (see Figure 4.7). The direct RF summed over all aerosol types is thought to be negative. Aerosols also indirectly cause a negative RF through the changes they cause in cloud properties, which are not shown in Figure 4.7. It has not been possible to explain the observed global temperature records for the 20th century with global climate models without a substantial post-World War II cooling term from the burning of sulfur-containing fossil fuels to partially offset the global warming from the CAPs. As nitrogen and sulfur oxides are reduced globally due to health and acid-precipitation concerns, their cooling effect will also be reduced, thus unmasking the climate warming due to other CAPs that they are currently counteracting.

In addition, as it is not possible to control BC emissions without simultaneously controlling the associated OC particle emissions from the same combustion sources, the global climate benefits of carbon-particle control measures, including improved combustion efficiency, depend on the ratio of BC to OC of each source. More recent observations and modeling (Ramanathan and Carmichael, 2008), however, indicate that the estimated warming of BC may be higher than those in the most recent IPCC estimates indicated in Figure 4.7. This would have policy implications because a much broader range of combustion sources would consequently have net climate benefits from combined control of BC and OC (Smith et al., 2009).

It is important to distinguish between direct and indirect RF. Direct RF results when the emitted substance is a greenhouse pollutant itself, such as CO_2. Indirect RF results when the emitted pollutant is not a greenhouse pollutant but takes part in chemical reactions to form a greenhouse pollutant or to change the global distribution of another greenhouse pollutant. SO_2, for example, is transformed in the atmosphere to form aerosol sulfates that act to produce a negative RF. NO_x emissions act to increase the oxidizing capacity of the troposphere, reducing methane (negative RF), but adding to tropospheric ozone (positive RF), while methane, carbon monoxide (CO), and non-methane volatile organic carbons (NMVOCs) contribute to O_3. Athough not emitted directly, nevertheless tropospheric ozone is the third most important human-influenced CAP in the atmosphere, as shown in Figure 4.7 (IPCC, 2007a).

As methane and carbon dioxide are well mixed globally, it is possible to treat emissions in all places and seasons as essentially equal, which led to the deployment of so-called "global warming potentials" by the IPCC, used to gauge the relative importance of emissions of different GHGs in treaties, inventories, and international carbon-offset programs. The complexity, short life, and local dependence of the short-lived CAPs, however, makes it difficult if not impossible to establish official "global" warming potentials for policy making. At present, therefore, they are not included in most international climate policy deliberations, although they are subject to much research and media attention and featured prominently in scientific assessments (Smith et al., 2009).

This gap is increasingly important as the world seeks to reduce global warming risks in ways that are both cost-effective and compatible with other goals, such as protection from outdoor air pollutants. In addition, control of the CAPs will not only have immediate health benefits, but much quicker climate benefits than control of CO_2. Not having a way to systematically look at co-benefits across the CAPs hampers these efforts. In addition, although the aerosols seem to have a net cooling effect, they can still impose regional climate impacts in South and East Asia, for example, and thus should not be considered benign (or beneficial) for the climate in addition to their important health consequences. Some have suggested, therefore, that regional climate disruption potentials might someday be applied to weight the relative importance of emission reductions for these CAPs.

4.11 Conclusions

4.11.1 Key Messages

- Most health impacts of today's energy systems come from the extraction and combustion of solid fuels. Some impacts are among workers collecting and processing coal and biomass. About 40% of the people in the world are exposed to household air pollution from the poor combustion of solid fuels used for heating, cooking, and lighting. This air pollution also contributes substantially to outdoor air pollution.

- Health impacts from most new and renewable energy sources are likely to be much smaller, but vigilance is needed to be sure these energy sources are managed carefully.

- Nuclear power poses low routine health risks to workers and the public if properly regulated. See Chapter 14 for a discussion of accident and proliferation risks.

- For long-term climate protection, CO_2 emissions need to be reduced through energy efficiency measures and a general shift away from fossil fuels. Shifting away from fossil fuel combustion may also proportionally reduce associated health-damaging pollutants, even if no special pollutant emission controls are used.

- Although energy efficiency measures are generally desirable, there are potential health impacts if done poorly, for example as a result of reduced home air exchange.

- Human-engendered climate change, which is largely but not entirely caused by energy use, seems already to be imposing health impacts, particularly among poor populations. Health impacts from climate change can be expected to steadily grow in the next decades unless major mitigation and adaptation efforts are undertaken.

- There are large health benefits from reducing carbon-containing aerosols, but the climate benefits are blunted somewhat because both BC aerosols (which are primarily warming) and OC aerosols (which are primarily cooling) usually decline together.

- There are climate, as well as health, benefits from reducing BC emissions, however, that may land on snow or ice, even if OC emissions are reduced as well.
- Per unit useful energy, the health benefits of emission reduction interventions rise as the combustion is closer to the population, i.e., as the intake fraction rises.
- Per unit useful energy, the health and climate benefits of emission reduction interventions rise with the fraction of incomplete combustion.
- Given the previous two conclusions and the widespread use of solid fuels in households, the largest co-benefit opportunities for health and climate lie in substituting away from solid fuels or increasing the solid fuel combustion efficiency in households. This is illustrated in Box 4.6.
- To capture the potential co-benefits for health and climate of changes in energy systems, society needs to make sure actions do not just shift the hazards from one population to another, e.g., shift the health burden from coal burning to a potentially even higher burden from nuclear proliferation.
- Using a life-cycle approach to evaluate energy sources, especially new and renewable fuels, is important to fully understand the health and climate costs and benefits across production, storage, transport, and end-use processes.
- The rush to find and implement ways to mitigate CAP emissions should not result in significant relaxation of the environmental and safety controls on new or existing energy systems, including those affecting outdoor air pollution, which were developed over the years to protect health.
- ILO and WHO guidelines for the protection of worker and public health should be adopted into law and enforcement practices worldwide.
- Control of primary and secondary aerosols may, in some cases, yield negative effects for either health or climate goals. For this reason, there is a need for multidisciplinary approaches to assessing and establishing aerosol policy goals, such that health and climate co-benefits can be maximized.

Energy systems play important roles in the burden of disease globally. GEA's estimates are that household air pollution from solid fuels was responsible for 2.2 million premature deaths in 2005 and outdoor air pollution was responsible for about 2.7 million premature deaths in the same year. Part of the latter can also be attributed to poor household

Table 4.12 | Rough contribution of energy systems to the global burden of disease, 2000.

Direct Effects [except where noted, 100% assigned to energy]	Total Premature Deaths – million	Percent of all Deaths	Percent of Global Burden in DALYs	Trend
Household solid fuel	1.6	2.9	2.6	Stable
Energy Systems Occupational*	0.2	0.4	0.5	Uncertain
Outdoor Air Pollution	0.8	1.4	0.8	Stable
Climate Change	0.15	0.3	0.4	Rising
Subtotal	2.8	5.0	4.3	
Indirect Effects (100% of each)				
Lead in vehicle fuel	0.19	0.3	0.7	Falling
Road traffic Accidents	0.8	1.4	1.4	Rising
Physical inactivity	1.9	3.4	1.3	Rising
Subtotal	2.9	5.1	3.4	
Total	5.7	10.1	7.7	

* One-third of global total assigned to energy systems

Notes: These are not 100% of the totals for each, but represent the difference between what exists now and what might be achieved with feasible policy measures. Thus, for example, they do not assume the infeasible reduction to zero traffic accidents or air pollution levels.

Source: Ezzati 2004.

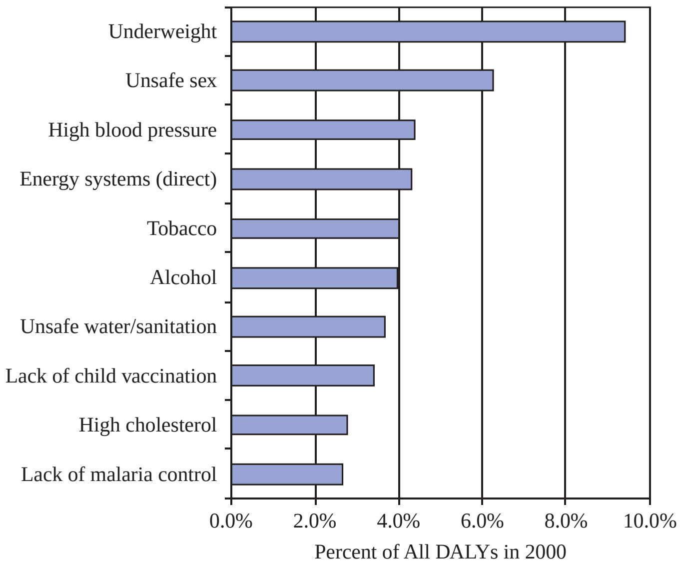

Figure 4.17 | Comparison of global burden of disease from major risk factors, including direct impacts of energy systems around the year 2000. Source: Table 4.12 and WHO Global Burden of Disease database (WHO, 2008).

Note: All expressed as a percentage of the total global burden in lost healthy life years (DALYs).

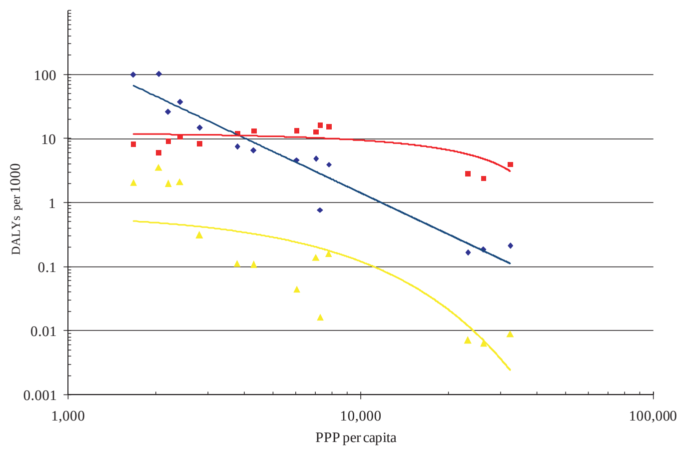

Figure 4.18 | Environmental risk transition: experienced burden of disease from environmental risk factors around 2000. Source: data based on Smith & Ezzati, 2005.

Notes: Household environmental risks (in blue), including pollution from solid fuel use, tend to decline with economic development, while community air pollution and traffic risks from energy use (red) first rise and then fall. Experienced risks from climate change (yellow) also tend to decline with development status. Vertical axis is in lost healthy life years (DALYs) per capita in each of 14 WHO epidemiological world sub-regions distributed by average income per capita. Note log scale on axes.

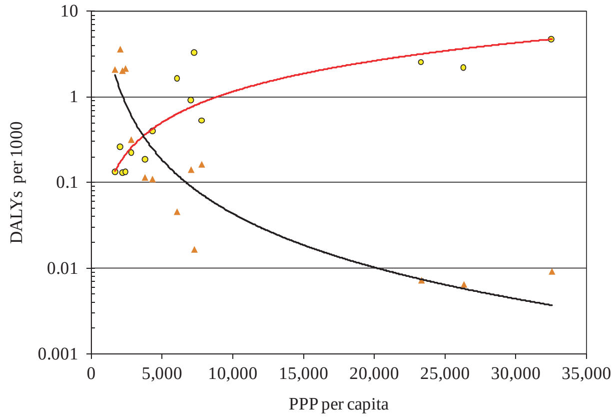

Figure 4.19 | Distribution of health impacts from climate change, experienced versus imposed, 2000. Source: data based on Smith & Ezzati, 2005.

Notes: Based on cumulative CO_2 emissions. Imposed health impacts from climate change (red line) rise with economic development. This is inverse of the pattern for experienced health impacts (black line), resulting in large inequities between rich and poor regions globally. Vertical axis is in lost healthy life years (DALYs) per capita in each of 14 WHO epidemiological world sub-regions distributed by average income per capita.

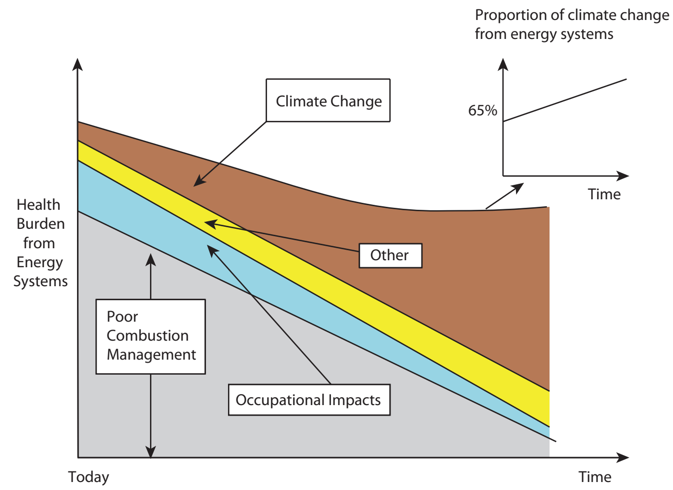

Figure 4.20 | Current trends in health impacts from energy systems.

Note: This represents a pessimistic future projection, in which combustion efficiency improves but effective climate policies do not exist.

fuel combustion. (Details on the calculations used to determine these figures can be found in Chapter 17.) Inclusion of energy's indirect role in lead pollution and occupational risks would probably add another 10–20% to that figure. Although outside the system boundaries of energy supply systems used in GEA, inclusion of road traffic accidents and energy's role in physical inactivity would roughly double these values. Recognizing the uncertainties of such calculations, the direct effects alone put energy systems above the global health impact of all other risk factors except malnutrition and unsafe sex and roughly equal to the global impacts of tobacco, alcohol, and high blood pressure based on WHO estimates for 2000 (see Table 4.12 and Figure 4.17). As noted in this chapter, the vast part of the direct impact comes from the poor management of fuel combustion.

Note these are not 100% of the totals for each, but represent the difference between what exists now and what might be achieved with feasible policy measures. Thus, for example, they do not assume the infeasible reduction to no traffic accidents or zero pollution levels.

Figure 4.18 shows how these energy system risks vary across the world by income level, illustrating what has been called the "Environmental Risk Transition" (Smith and Ezzati, 2005). Household-level risks tend to fall with economic development because they are so heavily influenced by household solid fuel use. Community (urban) risks, here including occupational impacts, form a more complex pattern by rising first during economic growth and then falling, roughly following what has been called the Environmental Kuznets Curve. Note, however, that there is much variation across the world in this pattern due to earlier or later introduction of policy measures. Experienced global risks due to climate change fall heavily on those living in poverty and thus also decline with development.

Figure 4.19 shows, however, that if global risks are distributed not by who experiences them but rather by who imposes them, the pattern is inverted. Poor countries receive much more impact than they have imposed in terms of their cumulative CO_2 emissions and rich countries impose much more than they experience. This has been called the "largest regressive tax in history."

Most of the health impacts of energy systems today are due to poor management of the combustion of fuels through emissions of incomplete combustion products and contaminants such as sulfur and nitrogen oxides. Second in importance are occupational impacts, particularly in the harvesting and processing of solid fuels. As world energy planning reorients toward reducing greenhouse emissions, there is need to take close account of the potential for doing so in ways that also continue to move society toward other important goals, such as those codified in the MDGs. Energy systems in general, not only have close links to CAP emissions, but in some cases to MDGs as well. In particular, household fuels are the system in which the two are most closely linked, with consequent opportunity to move both climate mitigation and health protection forward together. This is why providing access to clean household fuels and technologies is one of the major goals of the GEA scenarios in Chapter 17.

The health impact of climate change from energy use is relatively minor at present, partly because only about two-thirds of human-caused warming comes from energy systems (see Figure 4.20). The Figure assumes that the goals for the health indicators in the scenarios (Chapter 17) are met, which will mean very much lower health impacts from these two sources within a few decades. The impacts of climate change, however, are more refractory, partly because considerable climate change has already been committed and also because there is no sign at present that world society has found a way to grapple with greenhouse emissions effectively. In addition, as shown in the figure, the fraction of climate change due to energy systems will slowly rise under current trends. Shown in Figure 4.20, therefore, is a pessimistic outcome in which total health impacts from energy systems fall for some period as air pollution and occupational impacts come under control, but then start to rise as the health impacts from climate change begin in earnest. This outcome also depends, however, on the progress of society in dealing with the vulnerability of poor populations, since climate change operates mainly to enhance existing patterns of ill health. Thus, other scenarios than the one shown here are not only desirable but possible, albeit at considerable effort across several sectors.

Acknowledgements

11 April 2012

The authors are grateful for research assistance provided by Dr. Alfred Körblein and the, logistical assistance provided by Pat Wagner at IIASA. Zoë Chafe's participation in the IIASA Young Scientists Summer Program was enabled, in part, by a grant from the National Academy of Sciences Board on International Scientific Organizations, funded by the National Science Foundation (Grant No. OISE-0738129).

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