energy, the environment, and health

CHAPTER 3

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ABSTRACT About half of the world's households use solid fuels (biomass and coal) for cooking and heating in simple devices that produce large amounts of air pollution—pollution that is probably responsible for 4–5 percent of the global burden of disease. The chief ecosystem impacts relate to charcoal production and fuelwood harvesting.

At the workplace scale, solid-fuel fuel cycles create significant risks for workers and have the largest impacts on populations among energy systems. In communities, fuel use is the main cause of urban air pollution, though there is substantial variation among cities in the relative contributions of vehicles and stationary sources. Diesel-fuelled vehicles, which are more prominent in developing countries, pose a growing challenge for urban health. The chief ecosystem impacts result from large-scale hydropower projects in forests, although surface mining causes significant damage in some areas.

At the regional scale, fine particles and ozone are the most widespread health-damaging pollutants from energy use, and can extend hundreds of kilometres from their sources. Similarly, nitrogen and sulphur emissions lead to acid deposition far from their sources. Such deposition is associated with damage to forests, soils, and lakes in various parts of the world. At the global scale, energy systems account for two-thirds of human-generated greenhouse gas increases. Thus energy use is the human activity most closely linked to potential climate change. Climate change is feared to have significant direct impacts on human health and on ecosystems.

There are important opportunities for 'no regrets' strategies that achieve benefits at more than one scale. For example, if greenhouse gas controls are targeted to reduce solid fuel use in households and other energy systems with large health impacts (such as vehicle fleets), significant improvements can occur at the local, community, and global scales. ■

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Because of their ubiquity and size, energy systems influence nearly every category of environmental insult and impact.

The harvesting, processing, distribution, and use of fuels and other sources of energy have major environmental implications. Insults include major land-use changes due to fuel cycles such as coal, biomass, and hydropower, which have implications for the natural as well as human environment.[1] Perhaps the most important insult from energy systems is the routine and accidental release of pollutants. Human activities disperse a wide variety of biologically and climatologically active elements and compounds into the atmosphere, surface waters, and soil at rates far beyond the natural flows of these substances. The results of these alterations include a 10-fold increase in the acidity of rain and snow over millions of square kilometres and significant changes in the global composition of the stratosphere (upper atmosphere) and troposphere (lower atmosphere).

The rough proportions of various pollutants released into the environment by human activities are shown in table 3.1. Note the importance of energy supply systems, both industrial and traditional, in the mobilisation of such toxic substances as sulphur oxides and particles as well as in the release of carbon dioxide, the principal greenhouse gas. Also shown is the human disruption index for each substance, which is the ratio of the amount released by human activities to natural releases. This indicates that together with other human activities, energy systems are significantly affecting the cycling of important chemical species at the global scale. Although by themselves these indexes do not demonstrate that these insults are translated into negative impacts, their magnitudes provide warning that such impacts could be considerable.

In the past hundred years most of these phenomena have grown from local perturbations to global disruptions. The environmental transition of the 20th century—driven by more than 20-fold growth in the use of fossil fuels and augmented by a tripling in the use of traditional energy forms such as biomass—has amounted to no less than the emergence of civilisation as a global ecological and geochemical force.

The impacts from energy systems, however, occur from the household to the global scale. Indeed, at every scale the environmental impacts of human energy production and use account for a significant portion of human impacts on the environment.

This chapter examines the insults and impacts of energy systems according to the scale at which the principal dynamics occur—meaning the scale at which it makes the most sense to monitor, evaluate, and control the insults that lead to environmental impacts. After each scale is discussed, some cross-scale problems are considered to illustrate the need to control insults occurring at one scale because of the impacts they have at other scales. Impacts are divided into two broad categories: those directly affecting human health (environmental health impacts) and those indirectly affecting human welfare through impacts on the natural environment (ecosystem impacts).

Because of their ubiquity and size, energy systems influence nearly every category of environmental insult and impact. Indeed, large multiple-volume treatises have been devoted to discussing the environmental problem of just part of the energy system in single countries (as with U.S. electric power production in ORNL and RFF, 1994). A detailed review of the environmental connections of energy systems world-wide is beyond the scope of this volume. Indeed, simply cataloguing the routes of insults and types of impacts of energy systems world-wide would take substantially more space than is available here, even if accompanied by little comment.

In addition, for three other reasons reproducing catalogues involving simple listings of insults and impacts for each of the many types of energy systems would not serve the interests of readers. First, many detailed studies in recent years have done this job much better than we could here. Thus we will cite a range of such material to enable interested readers to expand their understanding. In addition, there is a substantial amount of such information in other chapters, for example, on the environmental and health impacts of renewable energy systems in chapter 7 and of fossil and nuclear power systems in chapter 8. Chapter 8 also addresses the technological implications of reducing urban pollution according to changes in local willingness to pay for health improvements. Chapter 1 discusses some of the relationships between environment and energy development, and chapter 9 has much discussion of the implications of various future energy scenarios for greenhouse gas emissions.

The second reason relates to our desire to help readers understand the relative importance of the problems. The significance of known environmental impacts from energy systems varies by orders of magnitude, from the measurable but minuscule to the planet-threatening. Just as the other chapters in this volume must focus on just a few of the most important energy system issues for the next half-century, we must do so for environmental impacts.

Finally, we feel that it is as important to give readers a framework for thinking about environmental impacts as it is to document current knowledge about individual problems. Thus we have devoted much of our effort to laying out the problems in a systematic manner using scale as the organising principle. Near the end of the chapter we also discuss two of the most common analytical frameworks for making aggregate comparisons involving a range of environmental impacts from energy systems: economic valuation and comparative risk assessment using fuel-cycle analysis.

Given space limitations and the reasons summarised above, we focus below on the two or three most important environmental insults and impacts at each scale. This approach brings what may seem to be a geographic bias as well—examples at each scale tend to be focused not only on the most important problems but also on the places in the world where the problems are most severe. We recognise that there are innumerable other impacts and places that could be mentioned as well, but we offer this set as candidates for those that ought to have the highest priority in the next few decades.

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Indeed, if these environmental problems were brought under control, the world would have moved most of the way towards a sustainable energy future from an environmental standpoint.

This chapter focuses almost entirely on the environmental insults and impacts associated with today's energy systems, in line with this report's goal of exploring the sustainability of current practices. In later chapters, as part of efforts to examine the feasibility of advanced energy conversion technologies, new sources of energy, and enhanced end-use efficiencies, the potential environmental impacts of future energy systems are explored.

TABLE 3.1. ENVIRONMENTAL INSULTS DUE TO HUMAN ACTIVITIES BY SECTOR, MID-1990S

Insult	Natural baseline (tonnes a year)	Human disruption index[a]	Share of human disruption caused by			
			Commercial energy supply	Traditional energy supply	Agriculture	Manufacturing, other
Lead emissions to atmosphere[b]	12,000	18	41% (fossil fuel burning, including additives)	Negligible	Negligible	59% (metal processing, manufacturing, refuse burning)
Oil added to oceans	200,000	10	44% (petroleum harvesting, processing, and transport)	Negligible	Negligible	56% (disposal of oil wastes, including motor oil changes)
Cadmium emissions to atmosphere	1,400	5.4	13% (fossil fuel burning)	5% (traditional fuel burning)	12% (agricultural burning)	70% (metals processing, manufacturing, refuse burning)
Sulphur emissions to atmosphere	31 million (sulphur)	2.7	85% (fossil fuel burning)	0.5% (traditional fuel burning)	1% (agricultural burning)	13% (smelting, refuse burning)
Methane flow to atmosphere	160 million	2.3	18% (fossil fuel harvesting and processing)	5% (traditional fuel burning)	65% (rice paddies, domestic animals, land clearing)	12% (landfills)
Nitrogen fixation (as nitrogen oxide and ammonium)[c]	140 million (nitrogen)	1.5	30% (fossil fuel burning)	2% (traditional fuel burning)	67% (fertiliser, agricultural burning)	1% (refuse burning)
Mercury emissions to atmosphere	2,500	1.4	20% (fossil fuel burning)	1% (traditional fuel burning)	2% (agricultural burning)	77% (metals processing, manufacturing, refuse burning)
Nitrous oxide flows to atmosphere	33 million	0.5	12% (fossil fuel burning)	8% (traditional fuel burning)	80% (fertiliser, land clearing, aquifer disruption)	Negligible
Particulate emissions to atmosphere	3,100 milliond	0.12	35% (fossil fuel burning)	10% (traditional fuel burning)	40% (agricultural burning)	15% (smelting, non-agricultural land clearing, refuse)
Non-methane hydrocarbon emissions to atmosphere	1,000 million	0.12	35% (fossil fuel processing and burning)	5% (traditional fuel burning)	40% (agricultural burning)	20% (non-agricultural land clearing, refuse burning)
Carbon dioxide flows to atmosphere	150 billion (carbon)	0.05[e]	75% (fossil fuel burning)	3% (net deforestation for fuelwood)	15% (net deforestation for land clearing)	7% (net deforestation for lumber, cement manufacturing)

Note: The magnitude of the insult is only one factor determining the size of the actual environmental impact.
a. The human disruption index is the ratio of human-generated flow to the natural (baseline) flow. b. The automotive portion of anthropogenic emissions in the mid-1990s is assumed to be 50 percent of global automotive emissions in the early 1990s. c. Calculated from total nitrogen fixation minus that from nitrous oxide. d. Dry mass. e. Although seemingly small, because of the long atmospheric lifetime and other characteristics of carbon dioxide, this slight imbalance in natural flows is causing a 0.4 percent annual increase in the global atmospheric concentration of carbon dioxide.

Source: Updated from Holdren, 1992 using Houghton and others, 1994; IPCC, 1996b; Johnson and Derwent, 1996; Lelieveld and others, 1997; Nriagu, 1989, 1990; Smithsonian Institution, 1996; Smith and Flegal, 1995; and WRI, 1998.

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Household scale

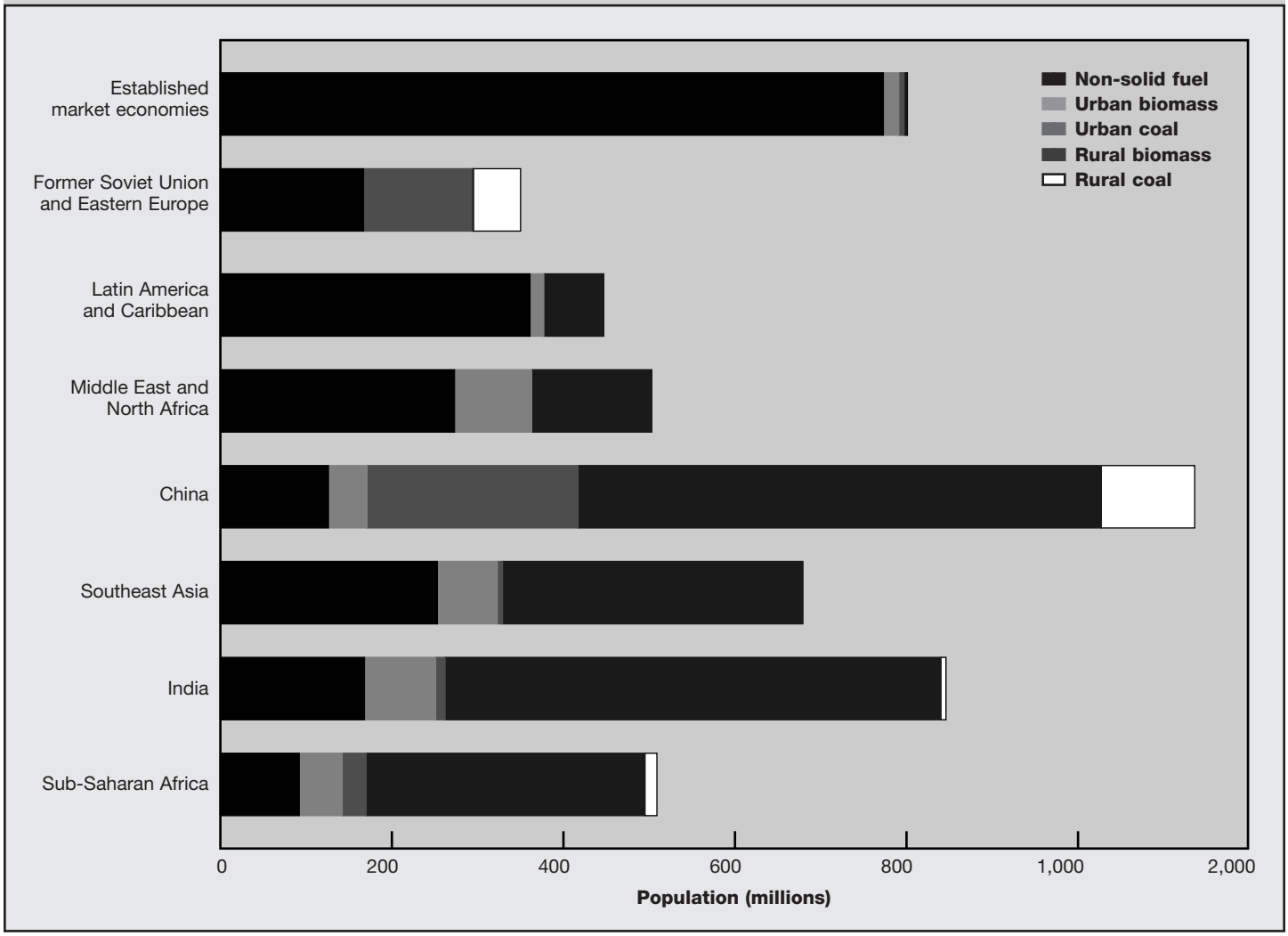
The oldest human energy technology, the home cooking fire, persists as the most prevalent fuel-using technology in the world. For much of the world's population, the home cooking fire accounts for most direct energy demand. Household fuel demand accounts for more than half of energy demand in most countries with per capita incomes under $1,000 (see figure 2.1).

The 'energy ladder' is a useful framework for examining trends and impacts of household fuel use (see figure 10.1). The ladder ranks household fuels along a spectrum running from simple biomass fuels (dung, crop residues, wood) through fossil fuels (kerosene and gas) to the most modern form (electricity). The fuel-stove combinations that represent rungs in the ladder tend to become cleaner, more efficient, more storable, and more controllable in moving up the ladder.[2] But capital costs and dependence on centralised fuel cycles also tend to increase in moving up the ladder (OTA, 1992).

Although there are local exceptions, history has generally shown that when alternatives are affordable and available, populations tend to move up the ladder to higher-quality fuel-stove combinations. Although all of humanity had its start a quarter of a million years ago at the top of the energy ladder in those times (wood), only about half has moved up to higher-quality rungs (figure 3.1). The remaining half is either still using wood or has been forced by local wood shortages down the ladder to crop residues, dung, or, in some severe situations, to the poorest-quality fuels such as shrubs and grass.

Throughout history in places where coal is easily available, local wood shortages have led some populations to move to coal for household use. This shift occurred about a thousand years ago in the United Kingdom, for example, although it is relatively uncommon there today (Brimblecome, 1987). In the past 150 years such transitions occurred in Eastern Europe and China, where coal use still persists

FIGURE 3.1. POPULATION AND HOUSEHOLD FUEL USE BY REGION, 1995



Source: Updated from Reddy, Williams, and Johansson, 1997.

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Physical form and contaminant content are the two characteristics of fuels that most affect their pollutant emissions when burned.

in millions of households (see figure 3.1). In terms of the energy ladder, coal represents an upward movement in terms of efficiency and storability. Because of these characteristics and its higher energy densities, it is possible to ship coal economically over longer distances than wood and to efficiently supply urban markets. In these senses, coal is like other household fossil fuels. Unlike kerosene and gas, however, coal is often a dirtier fuel than wood.

Harvesting

The chief environmental impacts of household fuel cycles relate to harvesting and combustion. In the 1970s books and newspapers called attention to the 'other' energy crisis, referring to the growing and alarming shortage of woodfuel affecting a large fraction of the world population that depended on it. Since deforestation and desertification were often also occurring in such places, it was perhaps a logical conclusion that fuel demand was to blame. It is still common today to read that deforestation is caused by fuel gathering in rural areas of developing countries. Detailed studies in many areas around the world, however, have rarely documented cases in which fuel demand is a significant cause of deforestation. The most important cause by far seems to be expansion of agricultural lands, followed by lumbering and road building. Indeed, the causation is more often the reverse—that is, the shortage of fuelwood is due to deforestation, rather than the other way around.

Part of the misunderstanding stems from the assumption that rural households gather woodfuel from forests. In many areas villagers gather significant amounts of fuelwood from what Gerald Leach has called 'invisible trees'—the trees around fields, next to houses, along roads, and so on that do not show up in most satellite remote sensing surveys or national forest statistics. Thus when estimates of local fuelwood demand appear to exceed growth rates in local forests, it does not necessarily imply that deforestation is taking place. Conversely, if deforestation is known to be occurring, it does not mean that fuel demand is necessarily the reason.

Similarly, desertification in the Sahel and elsewhere in Sub-Saharan Africa has links to fuel demand. But it has been difficult to separate out the influence of all the relevant factors, including climate change, intensification of grazing, land-use shifts, and fuel harvesting. Nevertheless, as with deforestation, there are some poor areas where harvesting of wood and brush plays an important role.

Although the link between fuelwood harvesting and deforestation is far from universal, there are localised cases in which fuelwood demand seems to contribute significantly to forest depletion. Most prominent among these are places, mainly in Sub-Saharan Africa, where commercial charcoal production is practised. In these areas temporary kilns (legal or illegal) in forested areas are used until local wood resources are depleted, then moved or rebuilt elsewhere. Charcoal, being a relatively high-quality and high-density fuel, can be trucked economically across long distances to urban markets. Thus large charcoal-using cities can have 'wood sheds' extending hundreds of kilometres along roadways, though there is evidence that significant regrowth often occurs over long enough periods. In some arid and semiarid areas, harvesting by woodfuel traders to meet urban demand seems to contribute to forest depletion, although, again, regrowth is often occurring. The quality of regrowth in terms of biodiversity and other ecosystem parameters is not well documented, however.

The harvesting of dung and crop residues as fuel does not have much direct environmental impact. But in some areas it may deprive local soils of needed nutrients and other conditioners. Indeed, in most rural areas the use of dung as fuel rather than fertiliser is probably a sign of poverty and lack of fuel alternatives. Crop residues, on the other hand, consist of a wide variety of materials, many of which do not have much value as fertiliser or soil conditioner. Indeed, in some cases disposal becomes a serious problem if these residues are not gathered for fuel. In these cases the usual practice is to burn the residues in place on the fields, with consequent pollution implications (although sometimes with benefits in terms of pest control). Consequently, regardless of development level, air pollution from post-harvest burning of farmland is a significant seasonal source of air pollution in many agricultural areas around the world (see chapter 10). Harvesting and preparation of household biomass fuels also have occupational health impacts on women and children, due, for example, to heavy loads and burns (see the section on workplace scale, below).

BOX 3.1. HEALTH-DAMAGING POLLUTANTS IN SOLID FUEL SMOKE FROM HOUSEHOLD STOVES IN INDIA

Biomass smoke
- Small particles, carbon monoxide, nitrogen dioxide.
- Formaldehyde, acrolein, benzene, 1,3-Butadiene, toluene, styrene, and so on.
- Polyaromatic hydrocarbons such as benzo(a)pyrene.

Coal smoke
- All the above plus, depending on coal quality, sulphur oxides and such toxic elements as arsenic, lead, fluorine, and mercury.

Combustion

Physical form and contaminant content are the two characteristics of fuels that most affect their pollutant emissions when burned. It is generally difficult to pre-mix solid fuels sufficiently with air to assure good combustion in simple small-scale devices such as household stoves. Consequently, even though most biomass fuels contain few noxious contaminants, they are usually burned incompletely in household stoves and so produce a wide range of health-damaging pollutants (box 3.1). Wood and other biomass fuels would produce little other than non-toxic products, carbon dioxide, and water when

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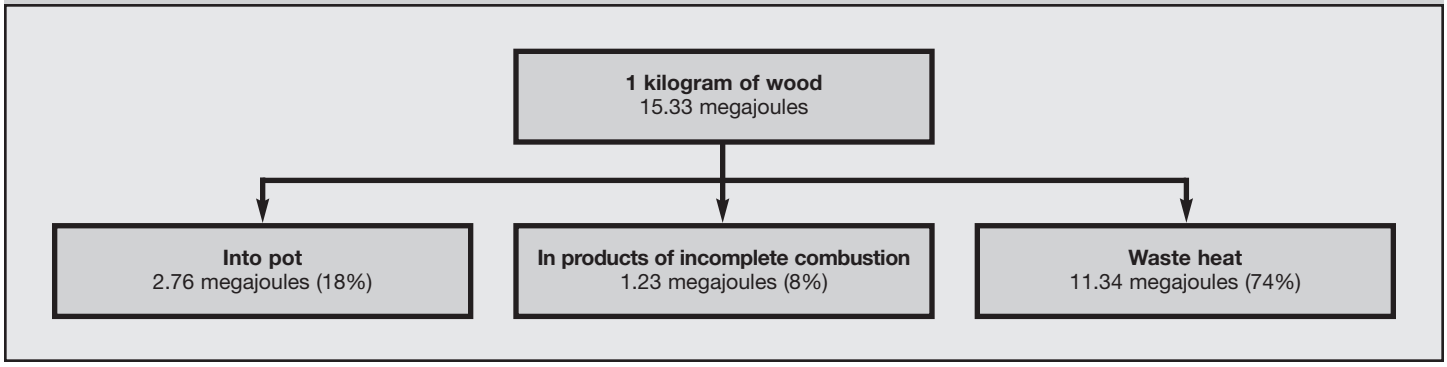
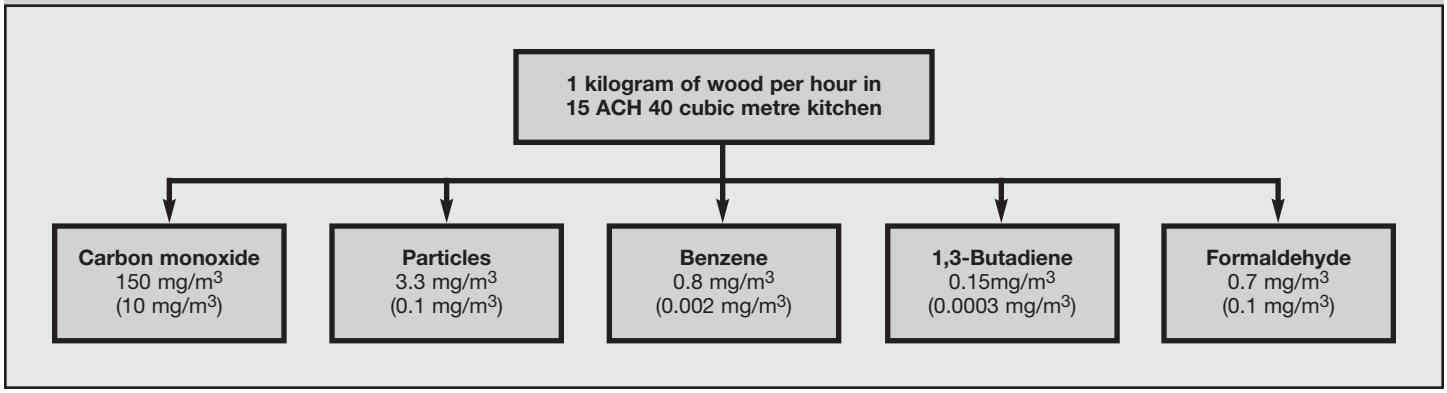
FIGURE 3.2A. ENERGY FLOWS IN A TYPICAL WOOD-FIRED COOKING STOVE



Source: Smith and others, 2000.

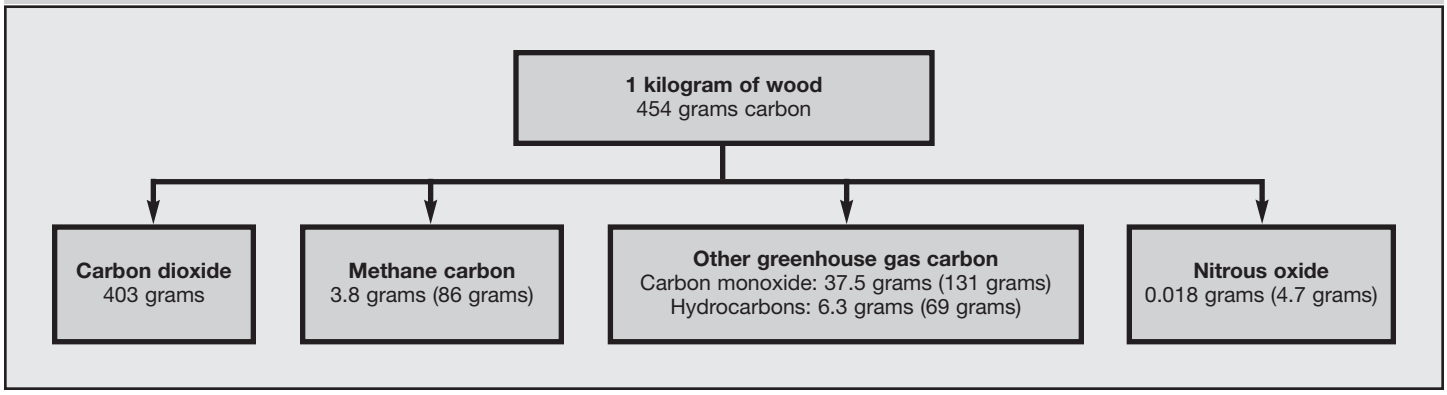
FIGURE 3.2B. INDOOR CONCENTRATIONS OF HEALTH-DAMAGING POLLUTANTS FROM A TYPICAL WOOD-FIRED COOKING STOVE



Note: Dozens of other health-damaging pollutants are known to be in woodsmoke. Mg/m^3 stands for milligrams per cubic metre. Numbers in parentheses are typical standards set to protect health.

Source: Smith and others, 2000.

FIGURE 3.2C. GREENHOUSE GAS EMISSIONS FROM A TYPICAL BIOMASS COOKSTOVE



Note: Numbers in parentheses are carbon dioxide equivalents of non-carbon dioxide gases.

Source: Smith and others, 2000.

combusted completely. But in practice sometimes as much as one-fifth of the fuel carbon is diverted to products of incomplete combustion, many of which are important health-damaging pollutants.

Coal, on the other hand, is not only difficult to burn completely because it is solid, but also often contains significant intrinsic contaminants that add to its emissions of health-damaging pollutants. Most prominent among such emissions are sulphur oxides (see box 3.1). But in many areas coal also contains arsenic, fluorine, and

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other toxic elements that can lead to serious health-damaging pollutants. Tens of millions of people in China, for example, may be exposed to such pollutants from household coal use.

Petroleum-based liquid and gaseous fuels, such as kerosene and liquefied petroleum gas, can also contain sulphur and other contaminants, though in much smaller amounts than in many coals. In addition, their physical forms allow much better pre-mixing with air in simple devices, assuring much higher combustion efficiencies and lower emissions of health-damaging pollutants in the form of products of incomplete combustion. Furthermore, stoves for petroleum-based liquid and gaseous fuels are much more energy efficient than those for coal. As a result emissions of health-damaging pollutants per meal from these fuels are at least an order of magnitude less than those from solid fuels (Smith and others, 2000).

Not only do solid-fuel stoves produce substantial emissions of health-damaging pollutants per meal, a large fraction do not have chimneys for removing the emissions from the home. Consequently, indoor concentrations of health-damaging pollutants can reach very high levels. Figure 3.2a shows the energy flows of a typical wood-fired cooking stove, in which a large fraction of the fuel energy is lost because of low combustion efficiency or low transfer of the heat to the pot. Figure 3.2b shows the excessive pollutant levels commonly reached in these circumstances, well beyond World Health Organization guidelines. Even in households with chimneys, however, heavily polluting solid-fuel stoves can produce significant local outdoor pollution. This is particularly true in dense urban slums, where such 'neighbourhood' pollution can be much higher than average urban pollution levels.

To estimate the health damage from pollution, it is necessary to take into account the amount of pollution released. Equally, important, however, is the behaviour of the population at risk. Even a large amount of pollution will not have much health impact if little of it reaches people. But a relatively small amount of pollution can have a big health impact if it is released at the times and places where people are present, such that a large fraction is breathed in. Thus it is necessary to look not only at where the pollution is but also at where the people are.

Unfortunately, pollution from household stoves is released right at the times and places where people are present—that is, in every household every day. This is the formula for high pollution exposures: significant amounts of pollution often released in poorly ventilated spaces at just the times when people are present. Moreover, because of their nearly universal responsibility for cooking, women and their youngest children are generally the most exposed.

Thus, although the total amount of health-damaging pollution released from stoves world-wide is not high relative to that from large-scale use of fossil fuels, human exposures to a number of important pollutants are much larger than those created by outdoor pollution. As a result the health effects can be expected to be higher as well.

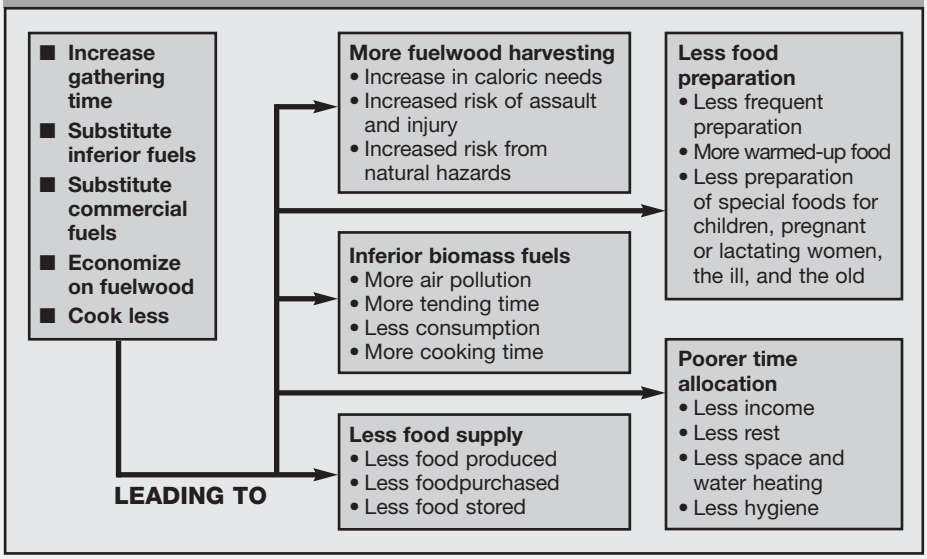
In many ways the harvesting impacts and air pollution from use of biomass fuels are the result of fuel shortages, particularly where inferior forms (dung and crop residues) are in use. Thus these can be considered part of the health effects of too little energy, along with lower nutrition and chilling (box 3.2).

BOX 3.2. HEALTH EFFECTS OF TOO LITTLE WOODFUEL

Lack of sufficient fuel for heating and cooking has several negative health impacts. First, in many places women and children must walk further and work harder to gather fuel, using more energy and time and placing themselves at increased risk of assault and natural hazards such as leeches and snakes. In addition, nutrition can be negatively affected if families have to walk long distances to gather cooking fuel. When seasonal changes result in longer fuel collection times, families are unable to compensate by reducing the time spent on agricultural activities. Instead the time is subtracted from resting and food preparation.

Inferior fuels, such as twigs and grass, that are used as substitutes in times of shortage require more attention from women during cooking, keeping them from other tasks. These fuels also produce more health-damaging smoke and are inadequate for processing more nutritious foods such as cereals and beans (since they have long cooking times). The figure at right outlines some coping strategies adopted by households to deal with fuel shortages and their health consequences.

Box figure. Household coping strategies for fuelwood shortages



Source: Agarwal, 1985; Brouwer, 1994.

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BOX 3.3. NATIONAL BURDEN OF DISEASE FROM HOUSEHOLD SOLID FUEL USE IN INDIA

National surveys, including the 1991 national census, show that nearly 80% of Indian households use biomass as their primary cooking fuel. As a result, a large portion of the Indian population is potentially exposed to indoor and outdoor levels of HDP produced by cooking stoves. Based on risks derived solely from studies of the health effects of individual diseases occurring in biomass-using households in developing countries, many in India itself, it is possible to estimate the total national burden of disease in India from use of these fuels:

Acute respiratory infection. More than a dozen studies around the world have found that household use of solid fuels is associated with acute respiratory infection in young children (although, as with all the diseases discussed here, there are other important risk factors, including malnutrition and crowding). Acute respiratory infection is the leading cause of death of the world's children and the largest category of ill health in the world in terms of disease burden. Almost 9 percent of the global burden of ill health and 12 percent of India's is due to acute respiratory infection. Acute respiratory infection linked to solid fuel use is estimated to cause 290,000–440,000 premature deaths a year in Indian children under 5.

Tuberculosis has been associated with household solid fuel use in a national survey in India involving nearly 90,000 households as well as in smaller studies. Although this relationship is not yet established with complete certainty, it would be highly significant because tuberculosis is on the rise in many developing countries due to HIV infection and the increase in drug-resistant strains. In India 50,000–130,000 cases of tuberculosis in women under 15 are associated with solid fuel use.

Chronic respiratory disease, such as chronic bronchitis, is almost entirely due to smoking in the industrialised world. But studies in Asia and Latin America have found the chronic respiratory disease develops in women after long years of cooking with solid fuels. In India 19,000–34,000 women under 45 suffer from chronic respiratory disease linked to solid fuel use.

Lung cancer, which is also dominated by smoking in industrialised countries, has been found to result from long-term exposure to cooking with coal in more than 20 studies in China. No such effect has been shown for biomass fuels, however. In India 400–800 women under 45 suffer from lung cancer linked to solid fuel use; the number is small because households rarely use coal.

Cardiovascular (heart) disease. Although there are apparently no studies in biomass-using households, studies of urban air pollution suggest that in India 50,000–190,000 women under 30 suffer from pollution-related heart disease.

Adverse pregnancy outcomes. Stillbirth and low birthweight have been associated with solid fuel use by pregnant women in Latin America and India. Low birthweight is a big problem in developing countries because it is a risk factor for a range of health problems. In India, however, there are too few studies to calculate the impacts of solid fuel use on adverse pregnancy outcomes.

Total. Because there is more uncertainty in the estimates for tuberculosis and heart disease, only the low ends of the estimated ranges are used. In India 410,000–570,000 premature deaths a year in women and children, of 5.8 million total, seem to be due to biomass fuel use. Given the age distribution of these deaths and the associated days of illness involved, 5–6 percent of the national burden of disease in women and young children can be attributed to biomass fuel use in households. For comparison, about 10 percent of the Indian national burden of disease is attributed to lack of clean water and sanitation.

Source: Smith, 2000; Smith and others, 2000, Murray and Lopez, 1996.

Estimated health effects

Considering the sizes of the relevant populations and the exposures to health-damaging pollutants, there has been relatively little scientific investigation of the health effects of indoor air pollution in developing countries relative to studies of outdoor air pollution in cities. Nevertheless, enough has been done to enable rough estimates of the total impact of air pollution, at least for women and young children (who suffer the highest exposures).

Three main types of health effects are thought to occur, based on studies in households that use solid fuels and corroborated by studies of active and passive smoking and outdoor air pollution (Smith, 1998):

- Infectious respiratory diseases such as acute respiratory infections and tuberculosis.
- Chronic respiratory diseases such as chronic bronchitis and lung cancer, and adverse pregnancy outcomes such as stillbirth and low birthweight in babies born to women exposed during pregnancy.
- Blindness, asthma, and heart disease.

The best estimates of such effects for developing countries have been done for India (box 3.3). These indicate that household solid fuel use causes about 500,000 premature deaths a year in women and children under 5. This is 5–6 percent of the national burden of ill health, or 6–9 percent of the burden for these two population groups.[3] This is comparable to, though somewhat less than, the estimated national health impacts of poor water and sanitation at the household level—and more than the national burdens of such major health hazards as malaria, tuberculosis, tobacco, AIDS, heart disease, or cancer (Murray and Lopez, 1996).

Given that India contains about one-quarter of the world's solid-fuel cooking stoves, the global impact could be expected to be about four times larger, or about 2 million deaths a year in women and children. This is roughly compatible with World Health Organization estimates of about 2.5 million, estimates that were generated by extrapolating studies from industrialised country cities to developing country conditions (WHO, 1997). The global burden of disease from major risk factors, including indoor air pollution, is shown in figure 3.3.

Greenhouse gases

The same incomplete combustion processes that produce emissions of health-damaging pollutants from household solid-fuel stoves also produce greenhouse gas emissions. (Greenhouse gas emissions and their global impacts are described below, in the section on the global scale.) A large amount of fuel carbon is typically diverted to gaseous products of incomplete combustion, all of which cause greater global warming per carbon atom than would be the case if complete combustion occurred and all the carbon was released as carbon dioxide (see figure 3.2c). The most powerful of these is methane, which over a 20-year period causes more than 20 times the global warming from the same amount of carbon as carbon dioxide (equivalent to a discount rate of about 4 percent).

Greenhouse gas emissions from several of the most important household fuels in developing countries (as measured in India) are shown in figure 3.4. Because of significant emissions of non–carbon

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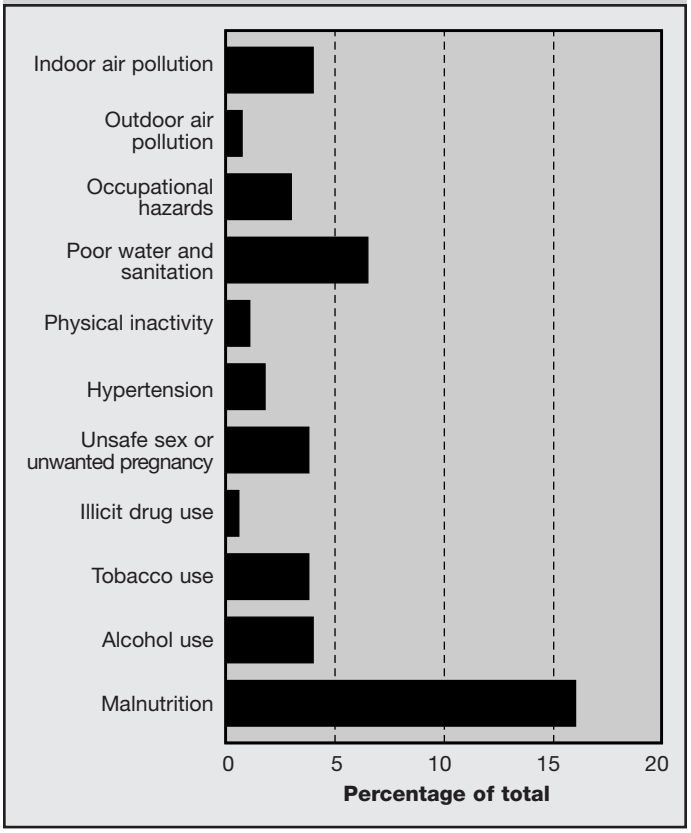
FIGURE 3.3. GLOBAL BURDEN OF DISEASE FROM SELECTED MAJOR RISK FACTORS, 1995



Note: Burden of indoor air pollution extrapolated from data for India.

Source: Smith, 2000; Murray and Lopez, 1996.

dioxide greenhouse gases, solid biomass fuels, even though renewable, have a larger greenhouse gas commitment per meal than fossil fuels, kerosene, and liquefied petroleum gas. These relationships have several important policy implications:

- Even if renewably harvested, many biomass fuel cycles are not greenhouse gas neutral because of their substantial production of products of incomplete combustion.
- In some situations, therefore, substitution of fossil fuels for renewable biomass might be recommended to reduce greenhouse gas emissions.
- To be greenhouse gas neutral, biomass fuel cycles must be based on renewable harvesting and must have close to 100 percent combustion efficiency (which most do not in their current configurations).
- Improved biomass stoves should be designed to increase overall efficiency and to reduce combustion inefficiency, which is the cause of greenhouse gas and health-damaging pollutants.

Stoves using biogas, which is made in household or village anaerobic digesters from dung (see chapter 10), have by far the least greenhouse gas emissions per meal—only about 10 percent of those for liquefied petroleum gas and a factor of 80 less than the average stove burning dung directly (see figure 3.4). A complete comparison of these fuel-stove combinations would require evaluating greenhouse gas emissions over the entire fuel cycle in each case, for example, including methane leaking from biogas digesters and releases from oil refineries making kerosene. Nevertheless, the extremely low greenhouse gas emissions from biogas stoves illustrate the potentially great advantage for greenhouse gas emissions of processed biomass fuels such as biogas. Such fuels can be both renewably harvested as well as burned as liquids or gases with high combustion efficiency. (The section on cross-scale impacts, below, discusses some of the potential opportunities for reducing impacts at the household and global scales through improvements in household cooking.)

Reducing the human health and global warming impacts of household stoves will require better stoves with higher efficiency, lower emissions, and cleaner fuels. These issues are discussed in chapter 10. Of course, the largest greenhouse gas emissions are from energy systems used in industrialised countries, as discussed in later sections.

Workplace scale

The extraction, transport, use, and waste management of energy sources involve important health hazards related to the work and workplaces involved in these activities. Many of the jobs involved, such as forestry and mining for solid fuels, are particularly dangerous. Many workers are engaged in these jobs, particularly in countries that are rapidly developing their industries and the energy sources that the industries require. In addition, much of the work needed for household energy supply in developing countries is carried out as a household task that does not figure in national statistics as an 'occupational issue'.

This section analyses these health issues based on the type of energy source and give examples of how the effects have been documented in different countries. The fourth edition of the International Labour Organization's *Encyclopaedia of Occupational Safety and Health* (Stellman, 1998) provides additional detail about energy jobs and their health hazards.

Biomass

As noted, wood, crop residues, dung, and the like are common energy sources for poor households in developing countries. Wood is also still widely used in industrialised countries, in some cases promoted in the interest of reducing greenhouse gas emissions. Wood and agricultural waste are often collected by women and children (Sims, 1994). Such collection is part of daily survival activities, which also include water hauling, food processing, and cooking (see chapters 2 and 10). An analysis in four developing countries found that women spend 9–12 hours a week on these activities, while men spend 5–8 hours (Reddy, Williams, and Johansson, 1997). Women's role in firewood collection is most prominent in Nepal (2.4 hours a day for women and 0.8 hours for men).

Firewood collection may be combined with harvesting of wood for local use in construction and small-scale cottage industry manufacturing. This subsistence work is often seasonal, unpaid, and not recorded in national economic accounts. Globally about 16

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Pollution from household stoves is released right at the times and places where people are present—that is, in every household every day.

million people are involved in forestry (Poschen, 1998), more than 14 million of them in developing countries and 12.8 million in subsistence forestry.

A number of health hazards are associated with the basic conditions of the forest. Forest workers have a high risk of insect bites, stings from poisonous plants, leech infestation, cuts, falls, and drowning. In tropical countries the heat and humidity put great strain on the body, while in temperate countries the effects of cold are a potential hazard. The work is outside, and in sunny countries ultraviolet radiation can be another health hazard, increasing the risk of skin cancer and eye cataracts (WHO, 1994). All forestry work is hard physical labour, with a risk of ergonomic damage such as painful backs and joints as well as fatigue, which increases the risk of injuries. Heavy loads of firewood contribute to ergonomic damage (Poschen, 1998). Women carrying heavy loads of firewood are a common sight in areas with subsistence forestry (Sims, 1994). Falling trees, sharp tools, dangerous machinery, and falls from heights are the main causes of injuries. In addition, the living conditions of forestry workers are often poor, and workers may be spending long periods in simple huts in the forest with limited protection against the weather and poor sanitary facilities.

Urbanisation 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 logs have been harvested. Energy forestry then becomes more mechanised, exposing workers to additional hazards (Poschen, 1998). Motorised hand tools (such as chain saws) become more common, resulting in high risks of injuries, noise-induced hearing losses, and 'white finger disease' caused by vibration of the hands. In addition, fertilisers and pesticides become part of the production system, with the potential for poisoning those who spray pesticides. As forestry develops further, more logging becomes mechanised, with very large machinery reducing the direct contact between workers and materials. Workers in highly mechanised forestry have only 15 percent of the injury risk of highly skilled forestry workers using chainsaws (Poschen, 1998). Still, firewood production remains an operation that requires manual handling of the product at some stage and so tends to remain hazardous.

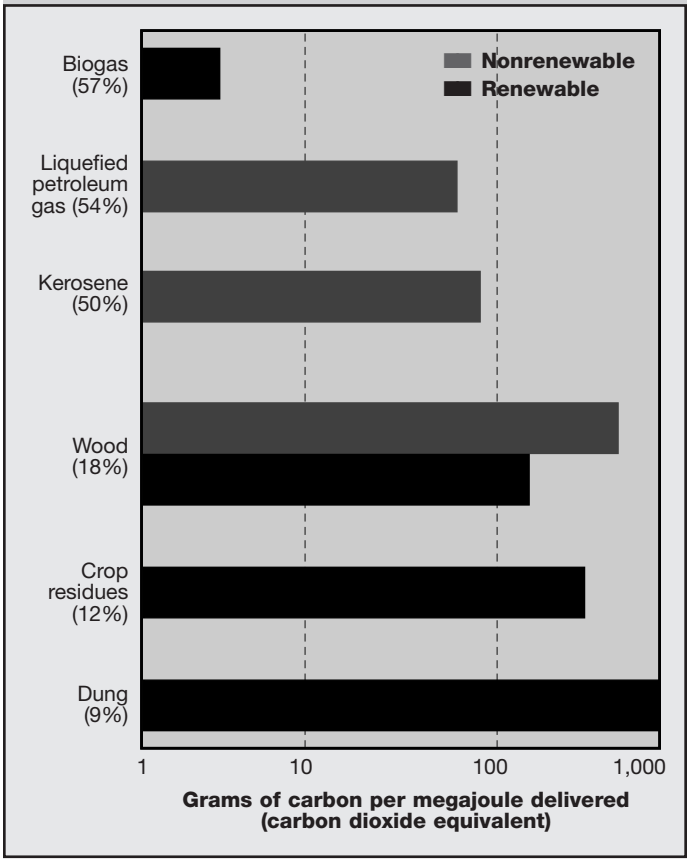
Another health aspect of wood-based energy is the risk of burning wood that has been treated against insect damage with copper-arsenic compounds or that has been painted with lead paint. Such wood may be harder to sell and so may be used to a greater extent by firewood production workers in stoves and open fires. When burned, poisonous arsenic and lead compounds will be emitted with the smoke. These compounds are health hazards when inhaled.

Coal

Coal is a major global energy source, accounting for 23 percent of total energy consumption. It was the primary energy source from 1900 until 1960, when it was overtaken by oil (WHO, 1997). Coal can be produced through surface (open cast) mining or underground mining. Like mining in general, both operations are inherently dangerous to the health of the workers. About 1 percent of the global workforce is engaged in mining, but these workers account for 8 percent of the 15,000 fatal occupational accidents each year (Jennings, 1998). Armstrong and Menon (1998) offers a detailed review of occupational health and safety issues in coal mining and other mining.

Underground coal miners are exposed to the hazards of excavating and transporting materials underground. These hazards include injuries from falling rocks and falls into mine shafts, as well as injuries from machinery used in the mine. There are no reliable data on injuries of this type from developing countries (Jennings, 1998), but in industrialised countries miners have some of the highest rates of compensation for injuries—and the situation is likely to be worse in developing countries. In addition, much of the excavation

FIGURE 3.4. GREENHOUSE GAS EMISSIONS FROM HOUSEHOLD FUELS



Note: Includes warming from all greenhouse gases emitted: carbon dioxide, methane, carbon monoxide, non-methane hydrocarbons, and nitrous oxide. Weighted by stove distribution in India. Numbers in parentheses are average stove energy efficiency. *Source: Smith and others, forthcoming.*

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Solid biomass fuels, even though renewable, have a larger greenhouse gas commitment per meal than fossil fuels, kerosene, and liquefied petroleum gas.

involves drilling into silica-based rock, creating high levels of silica dust inside the mine. Pneumoconiosis silicosis is therefore a common health effect in coal miners (Jennings, 1998).

Other health hazards specific to underground coal mining include coal dust, which can cause 'coal workers pneumoconiosis' or anthracosis, often combined with silicosis. Coal dust is explosive, and explosions in underground coal mines are a constant danger for coal miners. Coal inherently burns, and fires in coal mines are not uncommon. Once such a fire has started, it may be almost impossible to extinguish. Apart from the danger of burns, the production of smoke and toxic fumes create great health risks for the miners.

Even without fires, the coal material produces toxic gases when it is disturbed: carbon monoxide, carbon dioxide, and methane (Weeks, 1998). Carbon monoxide is extremely toxic because it binds to haemoglobin in the blood, blocking oxygen transport and creating chemical suffocation (Bascom and others, 1996). Carbon monoxide is a colourless and odourless gas and so gives no warning before the symptoms of drowsiness, dizziness, headache, and unconsciousness occur. Carbon dioxide, also colourless and odourless, displaces oxygen in underground air and can also cause suffocation. Another health hazard in mining is exhaust from the diesel engines used in underground machinery and transport vehicles. This exhaust contains very fine particles, nitrogen oxides, and carbon monoxide, all of which pose serious health hazards (Bascom and others, 1996). Exposure to fine particles in diesel exhaust increases the risk of lung cancer (Holgate and others, 1999).

Surface coal mining avoids some of the hazards of working underground. Still, it involves the risk of injuries from machinery, falls, and falling rocks. In addition, coal mining is energy-intensive work, and heat, humidity, and other weather factors can affect workers' health. The machinery used is also noisy, and hearing loss is a common among miners. Another health hazard is the often squalid conditions under which many coal workers and their families in developing countries live, creating particular risk for the diseases of poverty. In addition, such workers are likely to receive part of their compensation in the form of coal for use as household fuel, with consequent indoor and neighbourhood pollution.

After extraction, coal needs to be processed and transported to residential areas, power stations, and industries. 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 off-loading of large amounts of coal involves ergonomic, noise, and injury hazards.

The large-scale use of coal in power stations and industry creates yet more hazards. One is the conversion of coal to coke in steel-production. This process distils a large number of volatile polycyclic aromatic hydrocarbons in coal, the so-called coal tar pitch volatiles (Moffit, 1998). Exposure to these hydrocarbons puts coke oven workers at twice the lung cancer risk of the general population (IARC, 1984). (This process is not entirely associated with energy supply, as an important aim is to provide carbon to reduce iron oxides to elemental iron.) Additional health hazards are created for workers when the large amounts of ash produced by power stations and industry need to be transported and deposited. Crane (1998) reviews the health hazards faced by power generation workers.

Oil and gas

Oil and gas exploration, drilling, extraction, processing, and transport involve a number of the hazards as mining: heavy workload, ergonomic hazards, injury risk, noise, vibration, and chemical exposures (Kraus, 1998). This work is often carried out in isolated areas with inclement weather conditions. Long-distance commuting may also be involved, causing fatigue, stress, and traffic accident risks.

The ergonomic hazards lead to risks of back pain and joint pain. Injury hazards include burns and explosions. Skin damage from exposure to oil and to chemicals used in drilling creates a need for well-designed protective clothing. In addition, many oil and gas installations have used asbestos to insulate pipes and equipment. Inhalation of asbestos dust in the installation and repair of such equipment creates a risk of lung cancer, asbestosis, and mesothelioma (WHO, 1998a).

A lot of exploration and drilling for oil and gas occur offshore. This involves underwater diving, which is dangerous. In addition, weather-related exposures can be extreme, particularly since the work often requires round-the-clock operations (Kraus, 1998).

Hydropower and other renewables

Major hazards occur when a hydroelectric power station is built, because it usually requires constructing a large dam, excavating underground water channels, and building large structures to house the generator. McManus (1998) lists 28 occupational hazards potentially involved in the construction and operation of hydroelectric power stations. These include asbestos exposure, diesel and welding fumes, work in confined spaces or awkward positions, drowning, electrocution, noise, heat, electromagnetic fields, vibration, weather-related problems, and chemical exposures from paints, oils, and PCBs (polychlorinated biphenyls). As in any industry, however, proper attention to health and safety can keep the risks to acceptable levels.

The manufacture of wind and solar power equipment involves the typical hazards in manufacturing: injuries, noise, chemical exposures, and so on. In addition, the technologies for solar electricity generation involve new chemical compounds, some based on rare metals with poorly known toxic properties (Crane, 1998).

Nuclear power

Nuclear power generation has its own hazards due to the radiation hazards involved in mining, processing, and transporting uranium,

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as well as the radiation in nuclear power stations. In addition, occupational hazards will develop as countries start to deal with the backlog of radioactive waste. Due to the major potential risk to the general public from a malfunctioning nuclear power station, the safety of stations is always paramount. This has contributed to a low average occupational health risk for workers in the stations (Morison, 1998).

The mining of uranium has been an important occupational health hazard in nuclear power generation, as underground mining for uranium often entails high exposure to radon, a radioactive gas emitted form uranium. Radon exposure leads to an increased risk of lung cancer. In addition, the same occupational hazards in mining noted above occur, although the relatively high energy content of uranium ore means that there are fewer health effects per unit of electricity produced.

Until the Chernobyl accident, relatively few nuclear power station workers had been affected by radiation exposure. In that accident, however, 40 workers lost their lives in the fire or due to acute radiation exposure. The long-term impact on workers exposed during the accident in the form of cancer and other radiation-related effects is not yet known, however. The clean-up after the accident may eventually create substantially more effects. As many as 900,000 army, police, and other workers were called on to take part. Many workers were needed because they were only allowed to work for a short time, until they had reached the maximum allowable radiation dose. In some cases this dose was reached in a few minutes. Studies are now being undertaken to establish the exposure of each clean-up worker and the long-term health impacts (WHO, 1996).

Number of workers and quantitative health effects estimates

It is difficult to estimate the number of workers involved in meeting the energy requirements of communities. As noted, in poor communities much of this work is carried out by family members, particularly women, who are not formally employed. In addition, much of this work is carried out by small industries that are not always recorded in national employment statistics.

As noted, an estimated 16 million people are involved in forestry, most of them in developing countries. In industrialised countries with reliable statistics, the occupational mortality rate for agricultural workers is 5–10 times the average for all workers (Kjellstrom, 1994). Because of the additional risks in forestry, mortality rates for these workers are possibly twice as high again, or 32,000–160,000 at a global level. Not all of this activity is directly related to fuel demand, however.

As noted, miners are a large occupational group in international statistics (UN Demographic Yearbooks). They represent up to 2 percent of the economically active population in certain developing countries. Mining is an extremely dangerous occupation. Recent data show that occupational mortality rates for miners are up to 20 times the average for all occupations (ILO, 1998). The range of mortality rates may be as wide as that for forestry (2–10 per 1,000 workers per year). In most countries the economically active population is 40–60 percent of the population over 15. Thus miners may account for 1 percent of the population over 15, or about 30 million people world-wide. If half of these miners are coal miners, the number of miners killed each year in accidents would be about the same as for forestry workers (30,000–150,000). Another approach to this calculation is through total coal production. If applied to the world's coal production today, about 70 percent of which is in developing countries, the mean death rate in U.S. mines from 1890–1939 of 3.1 deaths per million tons produced would predict 16,000 coal mining deaths a year world-wide (ORNL and RFF, 1994a). This may be low, however, because China alone has about 6,500 coal mining deaths a year according to official statistics, which tend to be incomplete (Horii, 1999). The estimate of 6,500 of 16,000 deaths, on the other hand, is roughly consistent with China's 30 percent share of global production (BP, 1998).

For energy production and distribution as a whole, occupational mortality may sum to 70,000–350,000 a year. These numbers are likely to exclude many cases of occupational disease (such as cancers caused by asbestos or radiation) and deaths among the many workers in informal workplaces The upper limit of the numbers, however, may also be inflated by the crude estimates of mortality rates and number of workers. Occupational mortality rates in energy jobs in industrialised countries are generally 10–30 times lower than in developing countries (Kjellstrom, 1994; ILO, 1998), indicating that more effective prevention programs could eliminate more than 90 percent of the deaths referred to above. Still, energy-related jobs have inherent health risks that need to be considered when assessing the full impact of energy production and distribution.

Although too often ignored in discussions of environmental health risks, the burden of occupational disease and injury is substantial on a global scale. It is conservatively estimated that with well over 1 million deaths a year, nearly 3 percent of the global burden of ill health is directly attributable to occupational conditions (Leigh and others, 1996). This is substantial, accounting for more than motor vehicles, malaria, or HIV and about equal to tuberculosis or stroke. Although the fraction due directly to supplying energy is unclear, energy systems employ many millions of people world-wide in jobs substantially more risky than average—particularly in jobs producing solid fuels.

Community scale

Energy systems are associated with a vast array of insults and impacts (see table 3.1). Many of these are expressed at the community scale, including problems associated with coal and uranium mining, petroleum and gas extraction, water use and contamination by power plants, thermal pollution, and noise from wind farms. Here we can only focus on the largest of these impacts world-wide.

Urban air pollution is the chief environmental impact of energy systems at the community level. Although there are industrial and other sources of some pollutants, the vast bulk—whether measured

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About 1 percent of the global workforce is engaged in mining, but these workers account for 8 percent of the 15,000 fatal occupational accidents each year.

by mass or by hazard—is generated by fuel combustion or, as in the case of photochemical smog, is created in the urban atmosphere by precursor chemicals largely released in the course of fuel use. From the 1930s to the 1950s a number of urban air pollution episodes in the industrialised world brought air pollution to the attention of the public. The first major improvements came by banning the burning of refuse and coal within city limits. By the early 1970s the infamous London smogs (and their parallels in other cities), caused by coal combustion, were memories. Two other community-level impacts are also discussed in this section: those due to large hydroelectric dams and to nuclear power.

Fuel-derived air pollution in cities of industrialised countries

During the past 25 years the cities of the industrialised world have generally brought energy-derived urban air pollutants under even greater control. In the United States, for example, emissions per unit of useful energy from power plants and automobiles—the two largest urban energy polluters—have fallen65 percent and 50 percent in health hazard (weighted by the relative standards for each pollutant).[4] Japan and Western Europe have achieved similar results.

In the power sector these achievements have mostly come about by relying more on nuclear power and natural gas and by requiring smokestack controls for particles and nitrogen and sulphur oxides at coal-fired power plants. In addition, thermal power plants have become more efficient, and more improvements are expected, particularly for those using gas (see chapter 8). For vehicles, the reductions have come from a mix of improvements in engine combustion, increases in fuel efficiency (in North America), and the nearly universal requirement of catalytic converters (devices to help control pollutant emissions). Thus, despite significant increases in power production and vehicle use since 1975, overall emissions of most pollutants are now lower.

As a result of these emission reductions, urban air quality has generally improved throughout the industrialised world. Although fuel combustion produces a number of health-damaging pollutants, as explained above, small particles are probably the best single indicator. Suspended fine particles are a mix of primary combustion particles—carbonaceous materials and associated trace elements—and secondary conversion products such as sulphate and nitrate aerosols. In many parts of the world, windblown and urban dust can also be significant contributors to suspended fine particles.

Fine particles less than 2.5 micrograms in diameter are deposited deep in the lungs, where their clearance is slow and their ability to cause damage is enhanced. Fine particles also carry adsorbed trace metals and carcinogenic hydrocarbons into the lungs, intensifying the potential for health damage. Assessments of the human health effects of air pollutants increasingly focus on these fine particles. Still, there are few measurements of these fine particles in most cities, although more cities are measuring PM_{10} (particles less than 10 micrograms), which is considered a better indicator than simple total particulate levels (National Research Council, 1998).[5]

In the late 1990s the mean annual concentration of PM_{10} in North American, Western European, and Japanese cities ranged from 30–45 micrograms per cubic metre (figure 3.5). (The U.S. standard is 50 micrograms per cubic metre.) In the 1960s particulate levels were probably two to four times higher. (Small particles were not measured routinely until the mid-1980s, so previous levels have to be inferred from measurements of total particles.)

Still, industrialised countries face a number of energy-related air pollution challenges. Nitrogen dioxide and ozone levels exceed standards in many cities, particularly in sunny cities with large auto fleets such as Los Angeles (California) and Athens (Greece). In addition, recent evidence suggests that fine particles (less than 2.5 micrograms) may be better indicators of ill health than PM_{10}. This has led the United States to propose new regulations aimed at $PM_{2.5}$, potentially putting a number of cities out of compliance. European countries are also considering such regulations. Although long-term data are not widely available, there is little evidence of steady improvements in $PM_{2.5}$ levels in recent decades, partly because such particles are transported over much larger areas than larger particles.

This focus on even smaller particles has brought diesel exhaust particles under more scrutiny. Unlike gasoline, diesel produces a significant amount of particle emissions that are not only smaller but may have chemical properties that make them more dangerous (Cohen and Nikula, 1999). This feature raises questions about the future of diesel-fuelled vehicles, even though such vehicles can be slightly more fuel-efficient and cost-effective than gasoline-fuelled vehicles. The tendency for many countries to keep diesel prices low relative to gasoline—as a means of assisting farming, fishing, and other industries—can artificially promote diesel passenger vehicles. (See the section on cross-scale impacts, below, for a discussion of the economic implications of diesel particle health effects.)

Since the 1980s studies have seemed to indicate that there is no threshold for the health effects of particle pollution. In other words, there no longer seems to be an identifiable level that can be termed safe. All that can be said is that the effect is lower at lower levels, but does not seem to disappear even at the lowest (background) concentrations. Indeed, in the late 1990s European and global offices of the World Health Organization revised their particle guidelines to reflect the absence of thresholds (figure 3.6).

Because it is rarely (if ever) practical to set a standard of zero for pollutants with significant natural sources, standard setting is much harder for pollutants with no threshold for significant effects. Policy-makers must determine that the benefits of fuel combustion outweigh the extra mortality produced by the resulting pollution—for example, that the 5 percent increase in mortality 'allowed' by a PM_{10} standard of 50 micrograms per cubic metre above background

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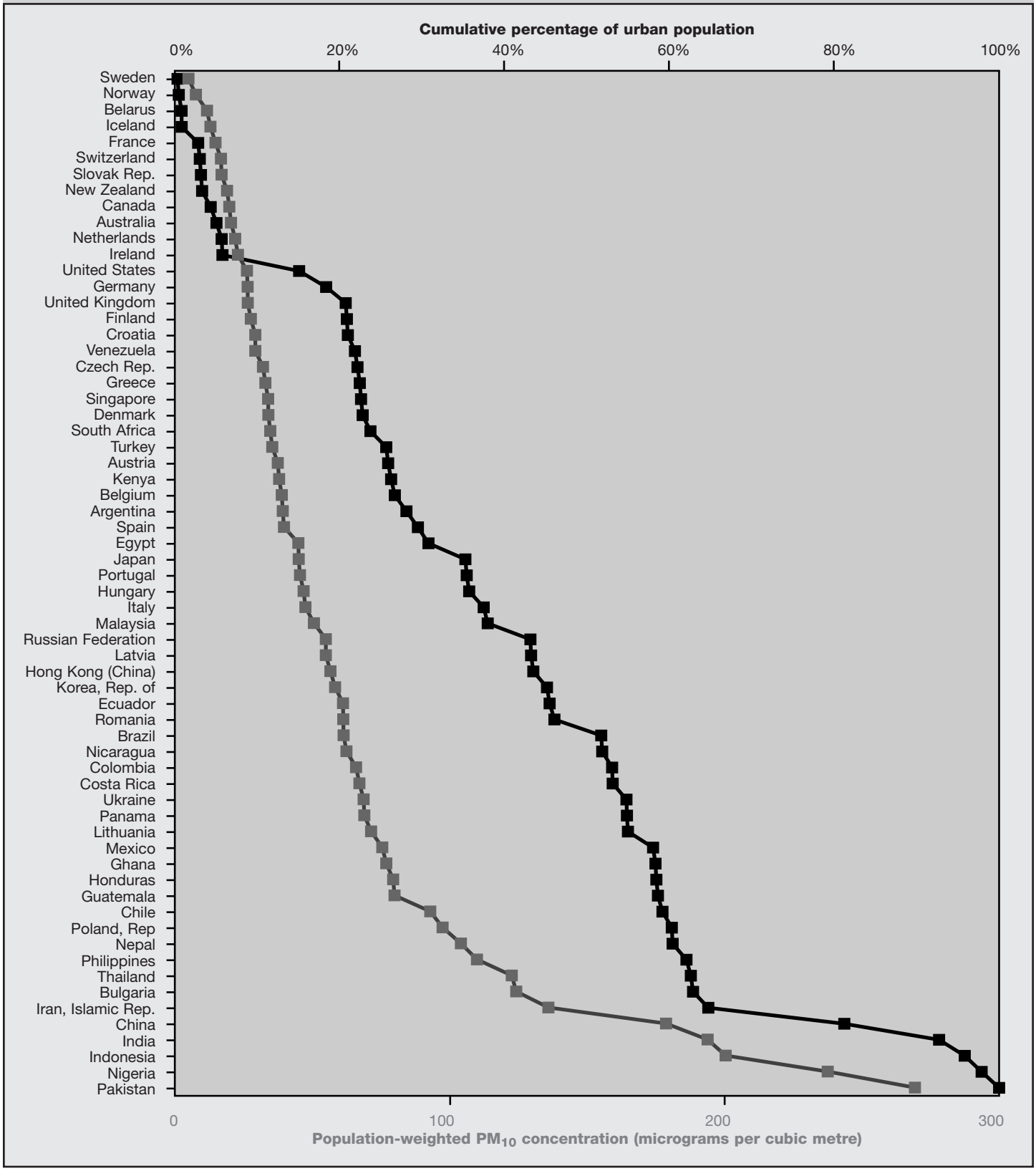
FIGURE 3.5. GLOBAL DISTRIBUTION OF URBAN PM_{10} CONCENTRATIONS



Source: WRI, 1998; WHO, 1998b.

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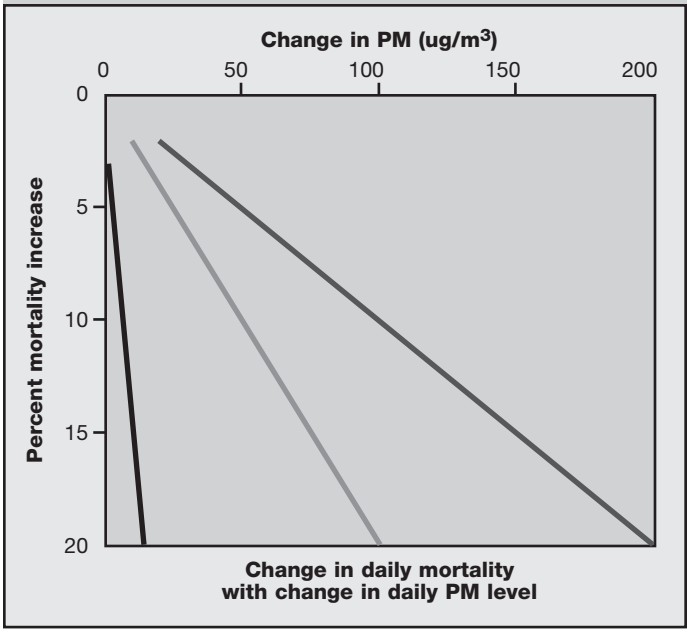
FIGURE 3.6. PROVISIONAL GLOBAL AIR QUALITY GUIDELINES FOR PARTICLES



Source: WHO, 1999.

(see figure 3.6) is acceptable given the societal advantages of fuel use. This is a difficult determination, and much more politically difficult than endorsing a standard that has some scientific validity of being below a 'no effects' level, which is how most standards are set. The likely result will be continuous pressure to tighten particle standards, with stronger incentives for lower particle emissions from vehicles, power plants, and other fuel-using sources. Indeed, as discussed in later chapters, emission reductions are the driving forces for new power and transport technologies.

As recently as the early 1990s, the main source of lead emissions throughout the world was tetra-ethyl-lead used as an additive to raise octane in gasoline. But nearly every country now has a plan to remove lead from gasoline (box 3.4). Still, significant numbers of children in many industrialised and developing countries have blood lead levels above those thought to affect cognitive development (intelligence). These levels will decline as lead is removed from the rest of the world's gasoline, although industrial and other sources must be controlled as well.

Fuel-derived air pollution in cities of developing countries

Developing country cities have much higher mean pollutant concentrations than industrialised country cities (see figure 3.5). In China and India cities, averages seem to be nearly 200 micrograms per cubic metre of PM10, though there is much variation by season and city. Such concentrations must be causing significant premature deaths—perhaps 15 percent or more above background levels. Indeed, estimates for premature mortality from urban air pollution

BOX 3.4. GETTING THE LEAD OUT: A SLOW SUCCESS STORY

"The current consensus is that no amount of Pb [lead] in the environment can be considered safe" (Schwela and Zali, 1999). Although this was not the first reason to remove lead from gasoline, it soon became the driving force. The introduction of catalytic converters spawned the need for unleaded gasoline to protect the devices. Shortly after, concerns about the health effects of lead emissions led to an increase in sales of unleaded gas and a reduction in the lead content of leaded fuel. Since leaded gasoline is responsible for about 90 percent of lead emissions, it was the most logical target for reduction (Lovei, 1998).

Many nations have taken action to phase out lead from fuel. Canada, Japan, and the United States have completely phased out leaded gasoline (Lovei, 1998; Schwela and Zali, 1999). Los Angeles (California) saw a 98 percent reduction in the lead exposure of commuters between 1979 and 1989. In Western Europe leaded gasoline has a very low lead content, and unleaded fuel has a large market share in most countries. In addition, a few developing nations have lowered or even banned lead in gasoline (Lovei, 1998).

Over the past 20 years Singapore has taken significant steps to phase out lead in fuel. Between 1980 and 1987 the lead content of leaded gasoline fell to a low 0.15 grams a litre. In 1991 unleaded petrol was introduced and taxes were changed to make it cheaper than leaded fuel. By the end of 1997 unleaded fuel accounted for about 75 percent of gasoline sales. In addition, more stringent exhaust emission standards were implemented for gasoline-fuelled vehicles, promoting an unleaded fuel market. Finally, oil companies agreed to phase out leaded gasoline by July 1998.

Mexico has also taken steps to reduce the lead content of fuel, though it still has far to go. Since 1994 the lead content of leaded fuel has been cut to 0.15 grams a litre. But it appears that the Mexican National Petroleum Co. has recently raised lead levels. No government agency has the authority to ensure fuel quality, making enforcement of low lead levels a challenge. Unleaded gasoline accounts for 46 percent of sales in Mexico City and 84 percent in Monterrey (which is wealthier and closer to the U.S. border). Leaded fuel is still cheaper, however. Mexico is implementing new standards requiring catalytic converters and so unleaded gas.

But large problems remain in many developing countries. The biggest lead problems are in Africa and in petroleum-exporting nations. These countries, including Venezuela and those in the Middle East, are dominated by powerful oil companies and state-owned refineries.

Although in 1994 two-thirds of global gasoline sales were unleaded, additional efforts are needed. Several mechanisms can encourage the reduction of lead in gasoline. The most promising is to set fuel taxes so that unleaded gasoline is cheaper than leaded fuel. Fuel filler inlets should be required in automobiles to allow only the narrower nozzles of unleaded fuel pumps to be used. Requiring catalytic converters in vehicles would further decrease the use of leaded fuel. Emphasising other benefits of using unleaded gasoline, such as lower exhaust emissions of hydrocarbons, also promotes the reduction of lead in gasoline (Schwela and Zali, 1999). Finally, as shown in Brazil, it is possible to substitute 5–10 percent ethanol for lead as an octane booster, thereby promoting renewable fuels.

An enduring urban myth exists that some older cars need lead to operate well. As long as the fuel has the correct octane level, no engine needs lead. Indeed, in many cases the removal of lead will have direct benefits in the form of less engine maintenance. The persistence of this myth slows the introduction of low-lead fuels despite technical evidence to the contrary.

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Dams affect Earth at scales rivalling other major human activities, such as urbanisation and road building.

range from 170,000–290,000 a year in China (World Bank, 1997; Florig, 1997) and 90,000–200,000 in India (Murray and Lopez, 1996; Saksena and Dayal, 1997).

The causes of air pollution in developing country cities are much more varied than in industrialised countries. Although automobile ownership rates are much lower, there tend to be many other types of vehicles as well, including two- and three-wheelers using highly polluting two-stoke engines. There also tend to be larger portions of light-duty and heavy-duty vehicles using diesel rather than gasoline. In addition to power plants and large industries with limited pollution controls, developing country cities tend to have large numbers of small boilers, engines, and open fires in the commercial and light-industry sectors, as well as in informal sectors such as street food. These enterprises tend to rely on the most inexpensive and thus dirty fuels in inefficient applications without pollution controls—and so have high emissions per unit of useful energy.

Furthermore, such cities often do not have adequate refuse and garbage collection, leading to street-side trash burning, a highly polluting activity. Even when collected, trash often burns uncontrollably in landfills in or near cities, wasting potential energy and producing clouds of noxious emissions. Another major non-energy source of particle pollution in many cities is dust from construction sites and unmanaged empty land. Finally, unlike in industrialised countries, a large fraction of urban households in developing countries still use solid fuels for cooking and space heating in inefficient stoves with no pollution controls (see figure 3.1). Although individually small, their large number means that these stoves can contribute significantly to urban pollution.

In addition to dealing with trash, dust, and other non-energy issues, the most pressing need for pollution control in developing-country cities is to reduce and eventually eliminate small- and medium-scale combustion of dirty fuels. For stationary sources, this means shifting away from solid fuels (coal and biomass) and high-sulphur fuels of any kind. For mobile sources, it means dealing soon with, in order of priority, two-stroke engines, poorly operating diesel engines, and gasoline-fuelled vehicles without catalytic converters. In addition, as is happening in Bangkok (Thailand) and New Delhi (India), there is great advantage in shifting vehicle fleets (taxis, buses, government vehicles) to clean-burning gaseous fuels such as compressed natural gas or liquefied petroleum gas (Mage and Zali, 1992).

Urban pollution control in the longer run

Because the best commercial technology in terms of energy efficiency and emissions has not been deployed completely in industrialised countries and has been used little in developing countries, much improvement is possible in the next 20 years without switching to advanced technologies. In the longer term, however, if air pollution levels are to be brought down to and kept at low levels given the projected increase in population, urbanisation, economic activity, and energy use, it will be necessary to develop and deploy new, even cleaner and more efficient energy-using technologies. A number of advanced power plant technologies potentially offer such performance (see chapter 8).

In addition, some near-commercial vehicle technologies may allow vehicle densities in developing country cities to grow for several decades and still meet air quality goals (box 3.5). Strong pollution controls will be needed to bring these technologies into wide use, however.

In addition to technical changes in vehicles of all types (not just private cars), a range of other improvements will be needed if the world's cities are to accommodate the greater demand for transport that increases in population and income will bring. These include improvements that result in significant and sustained enhancement in the attractiveness of public transport, land-use planning to reduce the need for intraurban trips, and implementation of policy tools such as time-of-day, congestion, and central-zone pricing. In addition, significant switches to public transport might occur though such means as including the cost of vehicle insurance in the price of fuel and taxing employer-provided parking as income (see chapter 11).

Hydroelectric dams

Dams, large and small, have brought tremendous benefits to many regions, including important contributions to development in industrialised countries. It is important not to deny these benefits t o developing countries. But such dams need to be designed and constructed with care. Although dams frequently serve many purposes—including flood control, irrigation, navigation, and recreation—major dams (those over 150 metres high, with 25 cubic kilometres of storage, or 1,000 megawatts of electricity) tend to have hydropower as one of the their main objectives. Such dams often have big impacts on the environment. There are more than 300 major dams world-wide, and nearly all have hydropower as a major component of their function. The environmental impact per unit of electricity production, however, can often be smaller for large than for small dams. The type rather than the size can be the most important factor (Gleick, 1992).[6]

With a total capacity of about 640,000 megawatts of electricity, hydropower provides about one-fifth of the world's electricity (Gleick, 1998). In Central and South America hydropower provides about 60 about of electricity; in Asia this figure is about 15 percent. Itaipu, on the border of Brazil and Paraguay, is the most powerful hydropower dam built to date, with a capacity of 12,600 megawatts of electricity. It cost $20 billion to build. When finished, China's Three Gorges dam will produce about 18,200 megawatts of electricity and may cost as much as $75 billion (*The Economist,* 1999). Thus hydroelectric dams are the most expensive energy projects in the world.

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No major river in the world is without existing or planned hydroelectric dams. Nearly four-fifths of the discharge of the largest rivers in Canada, Europe, the former Soviet Union, and the United States are strongly or moderately affected by flow regulation, diversions, and the fragmentation of river channels by dams (Dynesius and Nilsson, 1994). More than 500,000 square kilometres—the area of Spain—have been inundated by dam reservoirs world-wide, though not all for hydropower (Collier, Webb, and Schmidt, 1996). (Indeed, many hydropower plants have no reservoirs.) Globally, about 200 cubic kilometres of water a year—about 7 percent of the freshwater consumed by human activities—are evaporated from the surface of reservoirs due to their increased exposed surface area (Shiklomanov, 1998). Thus dams affect Earth at scales rivalling other major human activities, such as urbanisation and road building.

Direct human impacts. During the 20th century 30–60 million people were flooded off their lands by dams (Dunn, 1998). The World Bank, using Chinese government figures, estimates that 10.2 million people were displaced by reservoirs in China between 1950 and 1989 (World Bank, 1993). Given that a number of major dams are under construction or planned in developing countries, there will be no slackening in the pace of population displacement. China's Three Gorges Dam, for example, is expected is displace more than 1 million people, and the proposed Pa Mong Dam between Lao PDR and Thailand is expected to displace more than 500,000 (Gleick, 1998).

Large population resettlements can have a number of direct

BOX 3.5. ALTERNATIVE VEHICLES

With growing energy and environmental concerns surrounding today's conventional vehicles, a great deal of research is going into alternative vehicles. Four main types of alternative vehicles have the potential to reduce the environmental and efficiency deficits of conventional vehicles and to become commercially available in the near future.

Electric vehicles are powered by rechargeable batteries and have no internal combustion engines. The battery, which can be made of lead-acid, nickel-metal hydride, and lithium-polymer, can be recharged at home or, in the future, at recharging stations. Electric vehicles have several environmental benefits relative to conventional vehicles, including no tailpipe emissions and lower hydrocarbon, carbon monoxide, and nitrogen oxide emissions (including emissions from the production of electricity). Other advantages include lower maintenance costs and the elimination of the need for complicated tailpipe emission controls. But electric vehicles also have several disadvantages, such as the environmental concerns of an increase in electricity use, increasing emissions of sulphur oxides, and possible contamination from the disposal and recycling of batteries. There are also disadvantages in terms of convenience and cost, such as lengthy recharging and lack of infrastructure for recharging stations, short driving ranges (though electric vehicles are good for local trips and commuting for two-car households), an inability to maintain high speeds, and high battery costs. Today electric vehicles cost about $30,000, which is too expensive for most markets.

Hybrid electric vehicles combine the battery and electric motor of an electric vehicle with the internal combustion engine and fuel tank of a conventional vehicle, to obtain the benefits from both technologies. The engine, which is much smaller than that in a conventional vehicle, operates at a constant power load and so is more efficient, less polluting, and generates only the power required for most operations. Hybrid electric vehicles have several advantages over conventional vehicles and fewer disadvantages than electric vehicles. Hybrid electric vehicles have higher fuel economy and lower emissions than vehicles with internal combustion engines, and better range and more rapid refuelling than electric vehicles. Hybrid electric vehicles also reduce petroleum consumption and increase energy diversity by using alternative engines, which can use a range of fuels. But hybrid electric vehicles are still expensive and not yet fully developed. Programs are in place to develop and improve hybrid electric vehicles, and several automobile manufacturers are or will soon be marketing models.

Compressed natural gas vehicles are powered by an abundant, inexpensive fuel composed largely of methane. Natural gas is a clean-burning fuel with lower carbon dioxide, carbon monoxide, hydrocarbon, and nitrous oxide emissions than gasoline. This is partly due to the lower carbon content per unit of energy in natural gas relative to other fossil fuels. In addition to its environmental benefits, natural gas vehicles are cheaper to maintain, requiring service less frequently than conventional vehicles as well as having a lower cost of refuelling. Converting vehicle fleets such as taxis, three-wheelers, and buses to natural gas is an important interim way to improve air quality in developing country cities. Conversion costs are relatively small, although baggage space is reduced because of the need to add pressurised tanks. It is hard to use compressed natural gas for private vehicles because of the need to create many fuelling stations. Urban vehicle fleets, on the other hand, can operate with relatively few centralised fuelling stations.

Fuel-cell vehicles operate by combining hydrogen and oxygen gases into an electrochemical device, a cell, that converts them into water and electricity without using combustion. The hydrogen gas can come from a number of sources, including multiple forms of pure hydrogen and a variety of hydrocarbon fuels. Fuel-cell vehicles have many advantages over conventional vehicles. Fuel cells have a much greater engine efficiency and fuel economy, drastically reduce pollution emissions (including greenhouse gas emissions), and can use a wide variety of fuels, promoting energy diversity. In addition, they are quieter and smoother in operation, have tested at high performance levels, have long driving ranges, and have about the same operating costs as conventional automobiles. Still, there are several drawbacks to fuel-cell vehicles, including the lack of infrastructure to distribute hydrogen or another fuel (unless gasoline is used), difficult storage of pure hydrogen, and possible safety concerns. Major automobile companies are planning to have commercially available fuel-cell vehicles by 2004 and are currently demonstrating prototypes and improving on them. Large cost reductions need to occur, however, and fuel infrastructure issues must be resolved before fuel-cell vehicles are ready for the marketplace.

Of these four alternatives to conventional vehicles, electric vehicles have the fewest barriers to market entry. But they probably have the least consumer appeal in terms of environmental improvements and convenience. Fuel-cell vehicles will probably be found to be the most environmentally friendly, but they are the furthest from commercial development. Hybrid electric vehicles also offer a good option in the near future, with convenience and environmental benefits. All these cars will likely begin to enter the market in the next 5–10 years, and infrastructure will have to be built to accommodate all of them as well as today's automobiles.

Source: American Honda Motor Company, 1999; California Energy Commission, 1998; California Environmental Protection Agency, 1999; Ford Motor Company, 1998, 2000; General Motors Corporation, 1999; Global Toyota, 1999; Gould, and Golob, 1997; Hanisch, 1999; Krebs, 1999; Kremer, 2000; Mark, Obi, and Hudson, 1994; Matsumoto, Inaba, and Yanagisawa, 1997; Mendler, 1997; National Fuel Cell Research Center, 1999; Natural Gas Vehicle Coalition. 2000a, b; Neil, 1999; Steinbugler and Williams, 1998; USDOE, 1995; USEPA, 1994, 1998b.

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TABLE 3.2. ECOLOGICAL INSULTS AND IMPACTS OF LARGE DAMS

Insult caused by dam	Impacts seen	Severity of impact	Example of impact
Changes in the chemical properties of release water	Deterioration of downstream ecosystem cased by inability to process the increased dissolved minerals	Depends on the sensitivity of the affected ecosystem (tropical ecosystems are especially sensitive)	Enhanced algae growth in the reservoir consumes the oxygen in the epilimnion and, as it decays, the mass sinks to the already oxygen-deficient hypolimnion, where decay processes reduce the oxygen concentration even further, resulting in acid conditions at lower levels and the dissolution of minerals from the reservoir bed
Changes in the thermal properties of release water	Thermal pollution often results in species diversity reduction, species extinction, and productivity changes in the reservoir	Diversity, biomass, distribution, and density of fish stocks can be affected, disrupting breeding cycles	Productivity levels in the surface waters of new reservoirs often increase before long-term declines occur (Horne, 1994). China's Three Gorges dam may be the final critical factor for driving extinct the Yangtze River dolphin
Changes in the flow rate and timing of release water	Erosion increases downstream of dam. Settling of sediments in the reservoir causes high sediment loads to be picked up in the area immediately below the dam	Erosion of natural riverbeds can disturb the nurseries and spawning of many aquatic organisms, disturbing their breeding cycles	Changes in the downstream river morphology and ecosystem productivity
Changes in the sediment load of the river	High trap efficiencies of dams prevent the natural processes of sediments and associated nutrients refreshing downstream soils	Effects often noticed most severely in high-productivity areas downstream from the dam that no longer receive annual fertilisation	Before the Aswan High Dam was constructed, the Nile carried about 124 million tonnes of sediment to the sea each year, depositing nearly 10 million tonnes on the floodplain and the delta. Today 98 percent of the sediment remains behind the dam, resulting in a drop in soil productivity and depth, among other serious changes to Egypt's floodplain agriculture (Pottinger, 1997).
Changes in the dynamics of downstream riverbeds	Increased likelihood of lower water tables, which can create problems in areas near the dam where groundwater is a major source	Reduced access to potable water is a huge problem in many developing countries	Within nine years of the closure opening of the Hoover Dam, 110 million cubic metres of material had been washed away from the first 145 kilometres of riverbed below the dam (McCully, 1996)
Changes in the coastal area morphology	The loss of sediment in the rivers flowing through deltas and into the sea often results in a gradual process of delta and coastal degradation	Financially expensive for many areas where there is a large population living near the coastal zonecess of delta and coastal degradation	Over the past 80 years dams have reduced by four-fifths the sediment reaching the coasts of southern California. This has reduced the beach cover at the base of cliffs along these shorelines, causing cliffs to collapse (Jenkins and others, 1988).

social and health impacts. The social and cultural stress, loss of income, disruption of traditional support services, and other problems facing displaced populations often lead to lowered health status. Even when efforts are made to resettle people in new areas, it is difficult to locate land of similar productivity because other groups are likely to already occupy the best areas. Some 13,500 people have been swept to their deaths by the 200 or so dams (outside China) that have collapsed or been overtopped in the 20th century. In 1975 in Henan, China, about 230,000 people died from a series of dam bursts (Gleick, 1998).

Disease can spread from vectors that thrive in secondary dam systems, such as irrigation canals and even dam reservoirs. Mosquitoes carrying malaria, for example, have thrived in conditions created by dams. The parasitic disease schistosomiasis has also become more prevalent through the creation of habitats for snails that act as the disease vector. Nearby populations, for example, suffered nearly universal infection after several large African dams were filled, including Aswan, Egypt, Akosombo, Ghana, and Sennar, Sudan (Nash, 1993).

Ecosystem impacts. An internal survey of World Bank hydroelectric dam projects found that 58 percent were planned and built without any consideration of downstream impacts—even when these impacts could be predicted to cause coastal erosion, pollution, and other problems (Dixon, 1989). The main ecological insults and impacts of large dams (not just those producing hydropower) are summarised in table 3.2.

Dams and greenhouse gases. The work assessing the impacts of dams on greenhouse gas emissions is incomplete, but some estimates have been made. The most immediate changes are in the carbon flow between the flooded vegetation and the atmosphere. The decomposition of plants and soils causes the gradual release of their stored carbon (Rudd and others, 1993).

From a greenhouse gas standpoint, it might be thought that vegetation decaying in a reservoir would be no worse than the same amount of deforestation. Because of the low-oxygen conditions near and in the bottoms of many reservoirs, however, relative to deforestation a larger fraction of the biomass carbon is likely to be released as methane rather than as carbon dioxide. Since methane is a much

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more powerful greenhouse gas than carbon dioxide, the global warming impacts are greater than the same amount of carbon released as carbon dioxide.

The peak greenhouse gas emissions, however, are unlikely to rival those of a similarly sized fossil power plant, emissions from which would not decrease with age like those from a reservoir. In addition, it is difficult to determine the baseline in tropical forests—that is, how much methane and other non-carbon dioxide greenhouse gases are released in natural conditions. In colder climates reservoirs apparently emit greenhouse gases at much lower rates (Gagnon, 1998).

Nuclear power

There are two main environmental concerns about nuclear power, both mostly with regard to its potential impacts on human health. One involves the highly radioactive products produced by nuclear fission inside power reactors. Such products require careful management at the reactor and during and after disposal. The other concern revolves around the weapons-grade plutonium or uranium that might be clandestinely derived from the nuclear power fuel cycle to make bombs or other weapons of mass destruction by nations or subnational groups (see chapter 8).

The routine (non-accidental) emissions of pollutants from the harvesting, processing, and conversion of nuclear fuels are not negligible. And more than many technologies, they are vulnerable to being enhanced by mismanagement. Still, these emissions are generally substantially less than those involved with producing power with current coal technologies, the chief competitor in many areas. Although involving different pollutants, routine emissions from nuclear power systems are probably no more dangerous than those from new natural gas power systems—with the important exception of carbon dioxide, which is not produced by nuclear power. If public concerns about reactor safety, proliferation, and waste disposal can be satisfied, nuclear power may be able to play a significant role in de-carbonising the world energy system in the next 50 years (see chapter 8).

Regional scale

Nested between local-scale issues—such as the health effects of urban pollution—and global-scale issues—such as climate change—are a number of regional-scale problems that affect human health and ecosystems over areas the size of countries and continents. The most important regional-scale issues are acid deposition, tropospheric ozone, and suspended fine particles.

Matched with the regional spatial scale is a temporal scale that requires air pollutants to remain aloft for periods ranging from days to weeks and thereby be transported by prevailing winds and transformed by chemical reactions. Gases and fine particles meet this criterion; larger particles (greater than 1 micron or so in diameter) tend to settle out quickly and are considered contributors to local, rather than regional, impacts. Fine particles may be solid (such as elemental 'black' carbon) or liquid (such as aerosol droplets).

Contributing to regional pollution are a number of precursor species, most of which are generated by the use of fossil and biofuels. Prominent among them are sulphur dioxide (SO_2) and nitrogen oxides (NO_x). Sulphur dioxide is released during the combustion of the sulphur found naturally in fossil fuels, while nitrogen oxides originate either as fuel nitrogen or as atmospheric N_2 oxidised during combustion. Other species of importance are particulate matter (PM), carbon monoxide (CO), methane (CH_4), and non-methane volatile

TABLE 3.3. ANTHROPOGENIC EMISSIONS OF IMPORTANT SPECIES BY REGION, 1990 (MILLIONS OF TONNES)

Region	Sulphur dioxide		Nitrogen oxides		Carbon monoxide		Non-methane volatile organic compounds		Methane	
	Energy-related	Non-energy-related	Energy-related	Non-energy-related	Energy-related	Non-energy-related	Energy-related	Non-energy-related	Energy-related	Non-energy-related
Western Europe	8.8	2.5	3.6	0.4	45	23	10.1	7.6	5.5	18.0
Eastern Europe and former Soviet Union	13.5	3.4	3.5	0.6	47	36	13.9	6.2	37.6	20.3
North America	11.6	0.7	7.6	0.3	82	24	13.2	8.7	23.9	21.5
Asia	17.9	3.0	5.6	1.9	165	132	30.7	24.2	25.7	98.6
Rest of world	8.8	4.1	3.2	4.4	105	316	31.7	31.2	15.5	54.0
Total	60.6	13.6	23.5	7.6	444	531	99.6	77.9	108.2	212.3
		74.2		**31.1**		**975**		**177.5**		**320.4**

Note: These numbers are slightly different from those in table 3.1 because of different assumptions and methods. Energy-related sources include the combustion, extraction, processing, and distribution of fossil fuels and biofuels. Non-energy-related sources include industrial processes, deforestation, savannah burning, agricultural waste burning, and uncontrolled waste burning.

Source: Olivier and others, 1996.

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organic compounds (NMVOC), released during incomplete combustion and other activities. Ammonia (NH_3) is a significant regional pollutant, but fuel combustion is not its primary source.

When emissions of these primary species are released into the atmosphere, they form a complex, reactive 'soup', the chemical and physical behaviour of which is determined by such factors as temperature, humidity, and sunlight. The primary species are transported and deposited, influencing the health of humans and of natural ecosystems. But these primary species are also transformed into secondary species—such as sulphate, nitrate, acids, ozone, and miscellaneous organic compounds—that can have effects even more damaging than their precursors and in areas far removed from the primary sources. This can lead to transboundary problems, where a country or region has little control over the emissions that damage its environment.

Energy activities account for 82 percent of anthropogenic emissions of sulphur dioxide and 76 percent for nitrogen oxides.

Emissions and energy

A snapshot of global and regional anthropogenic (human-caused) emissions in 1990 is provided in table 3.3. The emissions are partitioned into those derived from energy-related activities (including combustion, extraction, processing, and distribution of fossil fuels and biofuels) and those derived from non-energy activities (which have a wide variety of sources, including industrial processes, deforestation, savannah burning, agricultural waste burning, and uncontrolled waste burning). Non-anthropogenic sources (volcanoes, soils) are not included.

Energy activities account for 82 percent of anthropogenic emissions of sulphur dioxide and 76 percent for nitrogen oxides. Energy activities play a less dominant role for the three other species—56 percent for non-methane volatile organic compounds, 46 percent for carbon monoxide, and 34 percent for methane. The smaller role of energy in emissions of these three species reflects the important contributions of deforestation, savannah burning, and agricultural waste burning in the generation of products of incomplete combustion, coupled with rice cultivation and enteric fermentation in the case of methane. Nevertheless, table 3.3 demonstrates the critical contribution of energy to emissions of regional-scale pollutants. It also highlights the importance of the developing world in current patterns of regional emissions.

Sulphur dioxide and nitrogen oxides play a role in the formation of acid deposition, because they can be transformed to acids in the atmosphere. The transformation products are fine particles, solid or aerosol, in the form of sulphates and nitrates. In addition, nitrogen oxides are a major precursor to the formation of regional tropospheric ozone. Finally, sulphates and nitrates have the ability to scatter and absorb radiation and so contribute to global and regional climate change, probably with a net cooling effect.

Carbon monoxide is an important regional atmospheric pollutant from several perspectives. It acts as an indirect greenhouse gas with a potential for global warming (see above, in the section on greenhouse) on a 20-year time horizon of about 4.5 due to its influence on the atmospheric lifetime of methane (IPCC, 1990). In addition, carbon monoxide is toxic to humans and is a critical component of many photochemical reactions in the atmosphere. It is a scavenger of hydroxyl radicals and so influences the production of ozone. There are many relatively easy ways to reduce carbon monoxide emissions—catalytic converters for automobiles, improved household stoves, and reuse of carbon monoxide gas in industry.

Non-methane volatile organic compounds consist of a variety of chemical species. In China, for example, the mix of organic compounds is 46 percent paraffins, 32 percent olefins, 21 percent aromatics, and 1 percent aldehydes (Piccot, Watson, and Jones, 1992). These compounds are important in the chemistry of the atmosphere because of their influence on the formation and destruction of ozone and methane. Non-methane volatile organic compounds are a product of the incomplete combustion of fossil fuels, biofuels, and other carbonaceous materials. They are also emitted during the extraction, processing, and handling of gaseous and liquid fossil fuels. And they are released through the evaporation of miscellaneous organic products in industry and households.

Ammonia is a significant component of regional emissions. Being an alkaline substance, it neutralises acids in the atmosphere. But once it is deposited on land, it can be converted to acid through biochemical processes in the soil. Ammonia emissions are largely derived from animal waste, fertiliser application, and fuel combustion. In 1990 energy-related activities accounted for just 5 percent of global ammonia emissions—2.7 of 52.0 teragrams (Olivier and others, 1998). Most ammonia emissions are from Asia and other developing countries, due to the rural nature of these countries, the intensive use of fertiliser for food production, and the heavy use of fossil fuels. In 1990 ammonia emissions in Asia were 22.5 teragrams, compared with 3.5 teragrams in Western Europe and 4.1 teragrams in North America.

Future emissions

Sulphur dioxide. The latest energy projections indicate that global sulphur dioxide emissions will likely stay roughly constant between 1990 and 2020, at about 59 teragrams of sulphur (Nakicenovic, Grubler, and McDonald, 1998). This 'middle-course' scenario incorporates modest economic growth, continued reliance on fossil fuels, and the elimination of trade barriers. At the regional level, however, a distinctive pattern emerges for all the important species. Emissions will decline in the industrialised regions of the Northern hemisphere—Europe, the former Soviet Union, North America—and increase sharply the developing regions of the Southern hemisphere and the Far East—Latin America, Africa, Asia (figure 3.7).

In Western Europe strong national environmental policies, changes in national energy policies, and implementation of the 1985 Helsinki Protocol and 1994 Oslo Protocol (under the 1979

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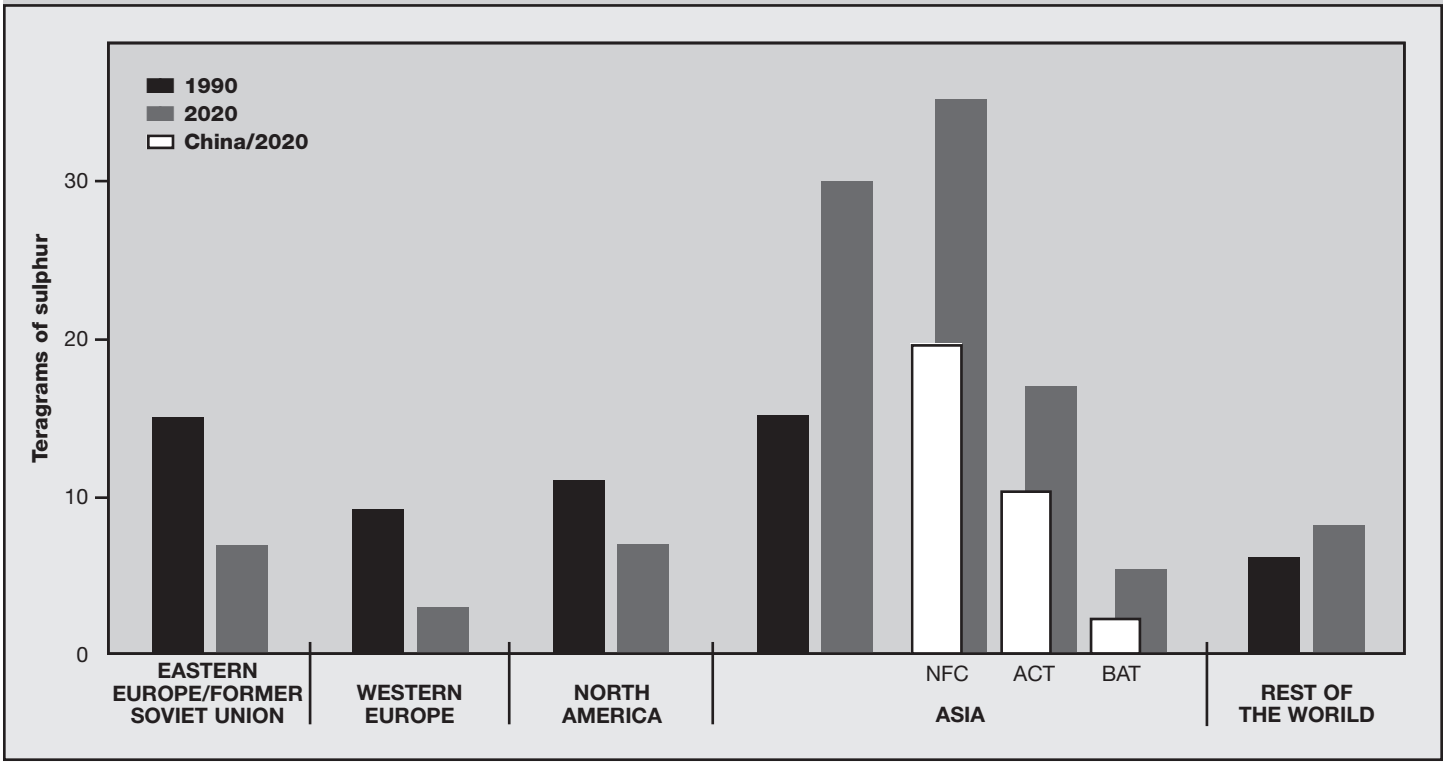
FIGURE 3.7. SULPHUR DIOXIDE EMISSIONS BY REGION, 1990 AND 2020 (PROJECTED)



Source: Nakićenović, Grüblrt, and McDonald, 1998; Foell and others, 1995.

Convention on Long-range Transboundary Air Pollution) have driven down sulphur dioxide emissions. As a result the region could see a 60 percent drop in sulphur dioxide emissions between 1990 and 2020. Similarly, in North America the adoption by the United States of the 1990 amendments to the Clean Air Act has reduced sulphur dioxide emissions. North America's sulphur dioxide emissions in 2020 are expected to be about 35 percent below 1990 levels. In Central and Eastern Europe and the former Soviet Union, a 50 percent reduction is anticipated.

The problem of sulphur dioxide emissions has shifted to the developing world, with emissions in Latin America, Africa, and the Middle East expected to increase by about 30 percent between 1990 and 2020. The main problem region is Asia, where emissions are already high—with 17 teragrams of sulphur emissions in 1990—and could double by 2020. If that happens, Asia will account for 58 percent of global emissions, much of them from China.

Three emission scenarios from the RAINS-ASIA model are also shown in figure 3.7 (Foell and others, 1995; Arndt and others, 1997; Streets and others, 1999). Driven by a similar energy forecast, the model projects that Asia's sulphur dioxide emissions in 2020 will be bounded by an upper value of 40 teragrams of sulphur (under the assumption of no further control policies beyond those in place in 1990—the NFC scenario) and a lower value of 6 teragrams of sulphur (with the assumption of very tight controls, similar to those in Western Europe). A mid-range estimate is 20 teragrams of sulphur, to be achieved if all large, new facilities are fitted with flue-gas desulphurisation units and other fossil-fuel users switch to low-sulphur fuels.

China continues to be the largest contributor to Asia's sulphur dioxide emissions, emitting about half of the continental total. But the establishment in 1997 of China's Two Control Zone policy for sulphur dioxide emissions has generated optimism that emissions will not grow as fast as once thought. Emissions of 11.9 teragrams of sulphur in 1995 are used as a baseline, and the plan is to limit national emissions to 12.3 teragrams of sulphur in 2000 by capping emissions in certain provinces at their 1995 levels. While implementation and enforcement questions linger, there is a commitment at the highest level in China to holding down sulphur dioxide emissions. The official (but undocumented) estimate for China's emissions in 2020 is 19.5 teragrams of sulphur.

The message from figure 3.7 is one of opportunity. With rapid growth in Asia, many of the coal-fired plants projected to be needed after 2000 have yet to be built. Thus the opportunity exists to fit these plants with emission controls or lower-emission technology at the time of construction. The incremental cost of emission reduction is then the only hurdle to be overcome—though it is a high hurdle ($25 billion a year for the ACT scenario, rising to $65 billion a year for the BAT scenario). Substitution of natural gas for coal is an attractive interim measure, and any possibilities for increasing the efficiency of energy use and moving towards renewable energy would reduce emissions of sulphur, nitrogen, and other species. The

ecologically driven scenario (chapter 9), for example, would lower global 2020 emissions from 59 teragrams of sulphur to 34 teragrams.

Nitrogen oxides. The situation for nitrogen oxide emissions is even more challenging, because of the added emissions from transportation. Though nitrogen emissions were not estimated by Nakicenovic, Grubler, and McDonald (1998), other analyses suggest a regional pattern similar to that of sulphur dioxide. An earlier study, *Energy for Tomorrow's World* (WEC, 1993), which was more optimistic about economic growth, forecast a 13 percent increase in global emissions of nitrogen oxide between 1990 and 2020 (from 24 teragrams of nitrogen to 27 teragrams) under case B assumptions. The increase in Asia was 70 percent (from 6.8 teragrams of nitrogen to 11.5 teragrams). Use of the RAINS-ASIA model, with its daunting view of the growth of fossil-fuel-based energy systems in Asia, yields an estimated increase of more than 300 percent in this period (van Aardenne and others, 1999).

Carbon monoxide and non-methane volatile organic compounds. Though there are no published projections for emissions of carbon monoxide and non-methane volatile organic compounds, carbon monoxide emissions are unlikely to increase in Asia, because inefficient combustion of biofuels will fall and inefficient vehicles will be replaced. On the other hand, emissions of non-methane volatile organic compounds may grow rapidly as expanding industrial production calls for greatly increased solvent use, increased vehicle use generates more hydrocarbons, and rising living standards increases the demand for domestic and commercial paints and solvents. Taken together, the expected rise in emissions of nitrogen oxides and non-methane volatile organic compounds bodes ill for the formation of regional ozone in the developing world.

Acid deposition

Acid deposition—or acid precipitation in its 'wet' form—is perhaps the most important regional-scale manifestation of energy generation through fuel combustion. Acid deposition occurs when sulphur dioxide and nitrogen oxides are oxidised in the atmosphere to s ulphuric acid (H_2SO_4) and nitric acid (HNO_3), respectively, and dissolved in rainwater. Clean rainwater is naturally acidic, with a pH of about 5.6. In the industrialised regions of Europe, North America, and Asia, rainfall pH values of 4.0-6.0 are common—and values as low as 3.0 have been measured in isolated events.

Acid deposition is a problem because it causes damage to natural and human-made surfaces with which it comes into contact. If soils contain insufficient alkali to neutralise the acid, damage can be caused to vegetation, particularly sensitive tree species and agricultural crops. Lakes can become acidified, leading to the demise of fish populations. Over time the entire natural structure and function of ecosystems can change. Manufactured materials can be attacked: metal surfaces rust, and alkaline materials like concrete, limestone, and marble are eroded (box 3.6).

In Europe forest damage has long been attributed to acid deposition. Despite emission reductions, the health of European forests still seems to be deteriorating (UNECE, 1996). In a 1995 survey of 117,000 trees in 30 countries, more than 25 percent showed signs of significant defoliation, and more than 10 percent showed significant leaf discoloration. Both direct and indirect effects of air pollution, of which acid deposition is but one part, are considered the cause. Surveys of forest soils show that, while sulphur deposition has dropped drastically since the 1970s, nitrogen deposition is still high, impairing soil chemistry and nutrient status. For acidification

BOX 3.6. ENVIRONMENTAL IMPACTS OF ACID DEPOSITION

In general, the exposure-response relationships between acid deposition and impacts on ecosystems, materials, visibility, and human health are complex. Some are reasonably well understood, but others involve poorly known relationships involving climate, geography, other chemicals, and time. Much research has been devoted to studies in North America and Western Europe, while relatively little has been done in Asia—where most of the growth in acid-depositing emissions is expected over the next few decades.

Acid deposition has harmful effects on many lakes and rivers, hurting aquatic life. In affected regions such as eastern Canada, lakes have acid levels that are unsafe for fish and other aquatic life. While species of fish vary in their sensitivities to acidification, those with low tolerance decline in population, at times to the point of extinction. This not only affects the species directly harmed, but loss of species diversity damages the ecosystem as a whole due to the interdependence among species (Curren and Nixon, 1992).

Although the impacts of acid rain on terrestrial systems are known with less certainty, several aspects are likely outcomes of acid deposition. Effects on soil include reducing the availability of nutrients and enhancing the solubility of metals. But nitrogen deposition into the soil can enhance its nutrient content, and some soils are fairly resistant to damage. Acid deposition can cause damage to foliage of trees and crops, however (Curren and Nixon, 1992). Forests, especially those at high elevations, are also affected by acid deposition directly through increased susceptibility to natural stresses and indirectly through a loss of nutrients obtained from soil (USEPA, 1999). Considerable uncertainty relates to long-term impacts that may not yet have been observed (NAPAP, 1998).

Several human health problems are linked to acid deposition. For example, many respiratory diseases, including bronchitis and emphysema, are likely caused or aggravated by sulphur particulates and nitrogen oxides. Respiratory problems are particularly noted in sensitive populations, such as children and asthmatics, as in Hong Kong, China (Hong Kong Municipal Government, 1999). Another potential human health problem comes from increased levels of toxic metals leached from soil, especially aluminium, into drinking water in rural areas (Environment Canada, 1999).

Acid precipitation is also known to have negative non-ecological consequences. It causes the erosion of materials and structures, leading to aesthetic and functional damage as well as increased maintenance costs. This damage to structures includes those that have a great deal of historical significance and are considered highly valuable. Another impact of acid deposition is haze, or a lessening of visibility, largely an aesthetic problem. (USEPA, 1999).

The largest documented economic disruptions have been to fishery, forestry, and agricultural industries. The damage occurring to their products is causing a loss of productivity and jobs (Environment Canada, 1999). Furthermore, recreational use of aquatic regions and forests has diminished, causing a loss in revenue (NAPAP, 1998).

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of surface waters, there appears to be an overall improvement (with higher pH, for example), probably as a result of reductions in acid deposition (UNECE, 1997). With projected reductions in sulphur and nitrogen emissions through 2020, continued progress is expected towards healthier ecosystems in Europe.

North America has seen significant reductions in the sulphate concentration and pH of precipitation as a result of the 1990 amendments to the Clean Air Act. Reductions in nitrate concentration have not been observed, however, because requirements for lower nitrogen oxide emissions did not go into effect until 1996 (NAPAP, 1998). On the whole, it is too early to tell if there has been significant improvement in the health of ecosystems. There is evidence of recovery in some New England lakes, but the U.S. Environmental Protection Agency has reported that additional reductions in sulphur and nitrogen deposition will be needed to fully restore the health of sensitive Adirondack lakes (USEPA, 1999). High-elevation spruce fir forests in the eastern United States continue to show signs of damage. But, as in Europe, there is reason to hope for improvement.

Asia is the region of greatest concern. Acid deposition is being reported throughout Asia (Wang and Wang, 1995), with many areas receiving levels that exceed the carrying capacity of their soils. Long-range transport is receiving scientific and political attention as countries receive increasing pollution from neighbouring and even distant countries (Huang and others, 1995; Ichikawa and Fujita, 1995; Streets and others, 1999). By far the worst episodes of acid deposition occur in southwestern China (Zhao and Xiong, 1988). Average rainwater pH values of 4.0–5.0 are observed in the Sichuan Basin, and values below 3.0 have been recorded in individual episodes. Atmospheric conditions in Sichuan and Guizhou provinces, with weak winds and frequent temperature inversions, are conducive to high pollutant concentrations. Emissions are also high there because of the widespread burning of high-sulphur coal in small stoves and medium-size industrial boilers.

Southwestern China has seen damage from acid deposition. Sulphur deposition levels are more than 10 grams of sulphur per square metre per year, making the situation comparable to the worst parts of the former Czechoslovakia in the 1960s and 1970s. Zhao and Xiong (1988) report the following effects in the vicinity of Chongqing and the provinces of Sichuan and Guizhou:

- A 50 percent dieback of pine forests on Nanshan Mountain, about 20 kilometres from Chongqing, attributed to acid deposition and air pollution.
- A more than 50 percent reduction in biomass production in commercial spruce forests in areas experiencing rain with a pH of less than 4.5.
- A yellowing of rice in large areas near Chongqing after rainfalls with a pH of less than 4.5.

Seip and others (1995) sampled soil water and stream water in a 7 hectare catchment near Guiyang in Guizhou Province, about 350 kilometres south of Chongqing. Sulphate concentrations were very high, pH values were as low as 4.3, and aluminium concentrations were elevated. Despite these factors, no apparent damage to vegetation was observed. It appears that neutralisation of acid inputs by deep soils and underlying bedrock may be averting ecosystem damage. Because of the heterogeneity of Chinese soils, however, local acidification and damage may be occurring in sensitive areas that have not been studied. A more recent survey of acidification in China by the Norwegian Institute for Water Research (Lydersen and others, 1997) reported severe effects of acid deposition on soils, water bodies with high loadings showing typical signs of acidification, and observed effects on surface water organisms.

Zhao and Xiong (1988, p. 342) describe some of the severe materials damage observed in Chongqing: "Metal structures are scraped of rust and painted once every 1–3 years. Shells of buses are generally replaced every 1–2 years. Structural components made of stainless steel become rusty after a few years. Some concrete works built in the 1950s have corroded in such a manner that the gravel is exposed. It is estimated that the corrosion depth reaches 0.5 cm in less than 30 years."

In northern China, by contrast, rainwater pH values are typically 6.0–7.0. Although emissions are high in many parts of northern China, meteorological conditions are more conducive to pollutant dispersion, and windblown dust from central Asian deserts tends to neutralise the acidity. The line delineating acid precipitation in China (pH of 5.6) extends just west of Beijing and along the eastern edge of the Greater Khingan mountain range. Since 1982 the area receiving acid deposition may have expanded by 600,000–700,000 square kilometres (Wang and Wang, 1995).

Acidification is responsible for much of the air pollution–related damage in China, though the relative roles of acid rain, dry deposition of sulphur dioxide, nitrates, particulates, ozone, and other factors have not been determined. Areas with lower rain acidity see much less damage than Chongqing and neighbouring cities of southwestern China. Acid rain damage to crops, forests, materials, and human health in China in 1995 is estimated to total more than $13 billion (*China Daily,* 9 March 1998).

In Asia there is also considerable concern about the fate of cultural materials as pollution levels rise. Concerns about the deterioration of the Taj Mahal were raised as far back as 1981 (Lal, Gauri, and Holdren, 1981). Throughout Asia, cultural buildings and monuments made of alkaline-based materials are vulnerable to attack. Glass, paper, textiles, and archives are also subject to accelerated deterioration in the warm, moist, polluted atmospheres of Asia. These problems are greatly under-appreciated and should be given high priority in future research before rich areas of cultural heritage are destroyed.

Finally, although not yet major emitters, Sub-Saharan Africa and Latin American have the potential for significant sulphur emissions as fossil fuel use increases.

Tropospheric ozone

Ozone is an important air pollutant that can cause damage to crops, trees, and human health. It is a major component of the harmful smog that forms in urban areas during periods of high temperature,

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Acid deposition is being reported throughout Asia, with many areas receiving levels that exceed the carrying capacity of their soils.

intense solar radiation, low wind speed, and an absence of precipitation. In the polluted air mass, ozone is produced by a complex set of chemical reactions involving nitrogen oxides and non-methane volatile organic compounds. North America and Europe are developing coordinated strategies to reduce emissions of ozone precursors and thereby reduce some of the health and ecosystem damage attributed to it. Although there is still progress to be made in these regions, it is again in Asia that concern is greatest.

Episodes of high ozone concentrations are now common in the megacities (cities containing more than 10 million people) of southern Asia that have industrial emissions (producing volatile organic compounds), transportation (producing nitrogen oxides), and conducive climates—Bangkok (Thailand), Hong Kong (China), Mumbai (India), and Shanghai (China), to name a few. In addition, the formation and transport of regional ozone have been observed in measurement campaigns such as PEM-West (Akimoto and others, 1996; Jaffe and others, 1996). Ozone concentrations were observed to be regionally enhanced by photochemical activity in continental air masses passing through areas with high nitrogen oxide emissions.

The potential effects of elevated ozone concentrations on human health and crop production in Asia are just beginning to be explored (Chameides and others, 1994). Studies in the West have established that crop yields are depressed by repeated exposures to ozone levels above 50–70 parts per billion; these concentrations are exceeded in fall and winter throughout large areas of southern China. There is concern that damage to winter wheat and other crops in the Yangtze Delta may endanger China's ability to meet increasing food demands. These analyses are still in their infancy, however, and much more work is needed on meteorological analysis, the gathering of monitoring data, field studies on crop responses to elevated concentrations, and regional assessments of economic impact. Until more of this work is done in Asia, a definitive statement cannot be made about the relationship between regional emissions of non-methane volatile organic compounds and nitrogen oxides and impacts on human health and vegetation.

Suspended fine particles

Particulate emissions are relatively well controlled in the industrialised world. Control systems on stationary and mobile sources are effective in limiting the release of primary particles, and secondary fine particles (such as aerosols) are being checked by reductions in emissions of their precursors. In the outdoor environments of many Asian cities, however, concentrations of fine particles are very high, exacerbated by domestic solid-fuel combustion, small-scale industrial activities, and inefficient transportation systems (see above). In many parts of the world the build-up of secondary fine particles over large regional areas during hot, dry spells leads to regional haze, impaired visibility, inhalation health effects, and related ecosystem problems.

Alkaline dust is also important in Asia because of its ability to neutralise the acidity of precipitation and deposition. In the spring (March, April, May) large dust storms build in the Taklamakan and Gobi deserts and the loess plateau areas of China and Mongolia. These storms are associated with strong cold fronts and prevailing westerly winds. Dust particles are lifted as high as 6 kilometres into the atmosphere and transported over long distances to eastern China, the Republic of Korea, Japan, the Pacific Ocean, and even North America. The dust contains high concentrations of calcium, which neutralises part of the acidity in rainfall. Thus, while sulphate levels in northeast Asian deposition are high and similar to those in North America and Europe, pH values are less acid (typically 5.3–7.0+).

Although large amounts of carbonaceous particles are emitted from the burning of coal, most of the larger particles fall to ground quickly and are not part of the regional emissions picture. Similarly, a large portion of particles is collected, for even in the most polluted regions some form of particulate collection is usually employed. Nevertheless, a certain portion of fine particles from fuel combustion is carried aloft and transported over long distances. These particles are usually less than 1 micron in diameter and consist of carbonaceous solids—so-called black carbon—and organic compounds in aerosol form. These particles can participate in chemical reactions, contribute to reduced visibility, and lead to soiling of surfaces. They scatter and absorb solar radiation and hence play a role in global warming. They also affect cloud albedo (ability to reflect sunlight), because their hydrophilic qualities increase the number of cloud condensation nuclei. On balance, black carbon is thought to contribute a net warming of about 0.5 degrees Celsius (C) globally (Penner, Ghan, and Walton, 1991).

The combustion of biofuels and coal in rural households and diesel fuel in vehicles is a prime contributor to these fine particles. There is an urgent need to better characterise the anthropogenic emissions of primary particles from Asian sources, both by size and chemical and physical characteristics. Diesel vehicles that are poorly designed, operated, and maintained emit large quantities of fine particles in much of the developing world.

Forest fires are a large source of particle emissions in all size ranges. Some of these fires are of natural origin (caused by lightning strikes), while others are caused by human activities such as forest clearing. The fires in Indonesia in the summer of 1997 caused a months-long regional air pollution episode in Indonesia, Malaysia, Singapore, and parts of Thailand and the Philippines. The health of tens of millions of people was affected. Increases in acute respiratory infections, asthma, and conjunctivitis were noted in Kuala Lumpur (Malaysia), Sarawak (Malaysia), and Singapore. Tests on school children in Malaysia noted significant decreases in lung function, the chronic effects of which will not be known for a long time (Brauer and Hisham-Hashim, 1998). Fine particles from such fires can be transported thousands of kilometres if atmospheric conditions are conducive.

Regional climate change

In the early 1990s it was recognised that sulphate aerosols can influence the global climate by scattering and absorbing incoming solar radiation (Charlson and others, 1992) and hence exerting a cooling effect. The role of sulphate aerosols has now been clarified (IPCC, 1996). Indeed, sulphate aerosols contribute negative radiative forcing (of about –0.4 watts per square metre) that offsets the positive forcing of carbon dioxide and other greenhouse gases. Hence a reduction in sulphur dioxide or nitrogen oxide emissions would be expected to reduce sulphate aerosol concentrations and increase the potential for global warming. The radiative forcing is spatially inhomogeneous, with values as large as –11 watts per square metre over heavily polluted areas such as Central Europe and eastern China.

Lal and others (1995) have suggested that sulphate aerosols can also interfere with local climates. The cooling effect of the aerosol haze reduces the difference between land and sea temperatures and weakens the monsoon. In addition, the cooler land surface reduces evaporation and lowers the amount of water vapour in the atmosphere. The authors estimate that sulphate aerosols in the Asian atmosphere will reduce monsoon rainfall over India and parts of China by the middle of the next century. The calculated reduction of 7–14 percent over the fertile north and central Indian plains would be a serious threat to agricultural production. It also appears that large-scale forest fires can reduce rainfall regionally.

Global scale: climate change from greenhouse gases

The two most important human-caused problems associated with environmental processes operating at the global scale are:

- The disruption of climate as the result of energy-related emissions of heat-trapping (greenhouse) gases with long atmospheric residence times.
- The depletion of stratospheric ozone as a result of emissions of chlorofluorocarbons and related compounds from air conditioning and refrigeration equipment (among other sources).

The character and origins of the first of these are discussed in this section. Stratospheric ozone is not addressed here because it is not primarily an energy issue, although it has connections to energy end-use technologies.[7]

It has been known since the work of Swedish scientist Gustav Arrhenius at the end of the 19th century that certain gases present in Earth's atmosphere in trace quantities exert a thermal blanketing effect that keeps the planet's surface much warmer than it would otherwise be. These are called 'greenhouse gases' because they work in a way analogous to one of the functions of the glass in a greenhouse, letting sunlight in but trapping outgoing heat by absorbing it and re-radiating some of it back to the ground.

The most important greenhouse gas naturally present in Earth's atmosphere is water vapour. Next in importance is carbon dioxide (CO_2), followed by methane (CH_4) and nitrous oxide (N_2O). The concentrations of these gases in the atmosphere before the start of the industrial revolution kept the mean global surface air temperature about 33 degrees Celsius warmer than it would have been in absence of an atmosphere with such natural levels of greenhouse gases. (This natural 'greenhouse effect' is highly beneficial to life on Earth, since without it the average temperature would be far below freezing.[8])

Although water vapour contributes the largest part of the natural greenhouse effect, its concentration in the atmosphere globally—on which the size of the water-vapour contribution to the greenhouse effect depends—is not significantly affected by emissions of water vapour from human activities. The most important anthropogenic greenhouse gas emissions are those of carbon dioxide (CO_2), which arise mainly from combustion of fossil and biomass fuels and from deforestation (see below).[9, 10] An important indirect effect of human activities on the atmospheric concentration of water vapour results from increased evaporation of water from the surface of Earth because of the warming caused by increasing concentrations of anthropogenic greenhouse gases in the atmosphere. The resulting increase in atmospheric water-vapour content further warms Earth's surface—a significant 'positive feedback' in the anthropogenic greenhouse effect.[11]

Concerns developed many decades ago that human-caused increases in the carbon dioxide content of the atmosphere might accentuate the natural greenhouse effect enough to disturb the global climatic patterns to which human habitation, agriculture, forestry, and fisheries had become accustomed. As a result, in 1958 scientists began to take direct measurements of the atmospheric concentration of carbon dioxide at locations far from its main human sources.[12] The continuous record of such measurements, at various remote locations on land and from ships and aircraft, has revealed a steady increase in the global atmospheric inventory of carbon dioxide, reaching 14 percent above the 1958 level by 1995.

Reconstruction of the earlier history of atmospheric carbon dioxide content (by analysis of air bubbles trapped in layered cores taken from polar ice sheets) has established that the increase from pre-industrial times to 1958 was about 13 percent. Thus the ratio of the 1995 concentration to the pre-industrial one is 1.14 x 1.13 = 1.29, representing an increase of 29 percent (figure 3.8). The rise in the atmosphere's inventory of carbon dioxide closely tracks the rise in global fossil-fuel burning over the past 150 years. Moreover, studies based on relatively abundant carbon isotopes confirm the role of fossil-fuel-derived carbon in the observed increase. There is reason to believe that the slower increase in the 100 years before that was due mainly to widespread deforestation for timber, fuelwood, and charcoal.

Not all of the carbon added to the atmosphere by human activities stays there. A substantial part is absorbed by dissolution into the surface layer of the world's oceans (from which oceanic mixing processes gradually transport the dissolved carbon dioxide into the much larger volume of water in the deep oceans). And part is absorbed into forests and soils in areas where the forest 'standing crop' or soil carbon inventory are growing.[13] Estimates for the balance of sources, sinks, and atmospheric accumulation of anthropogenic carbon during the 1980s are summarised in table 3.4. The mean

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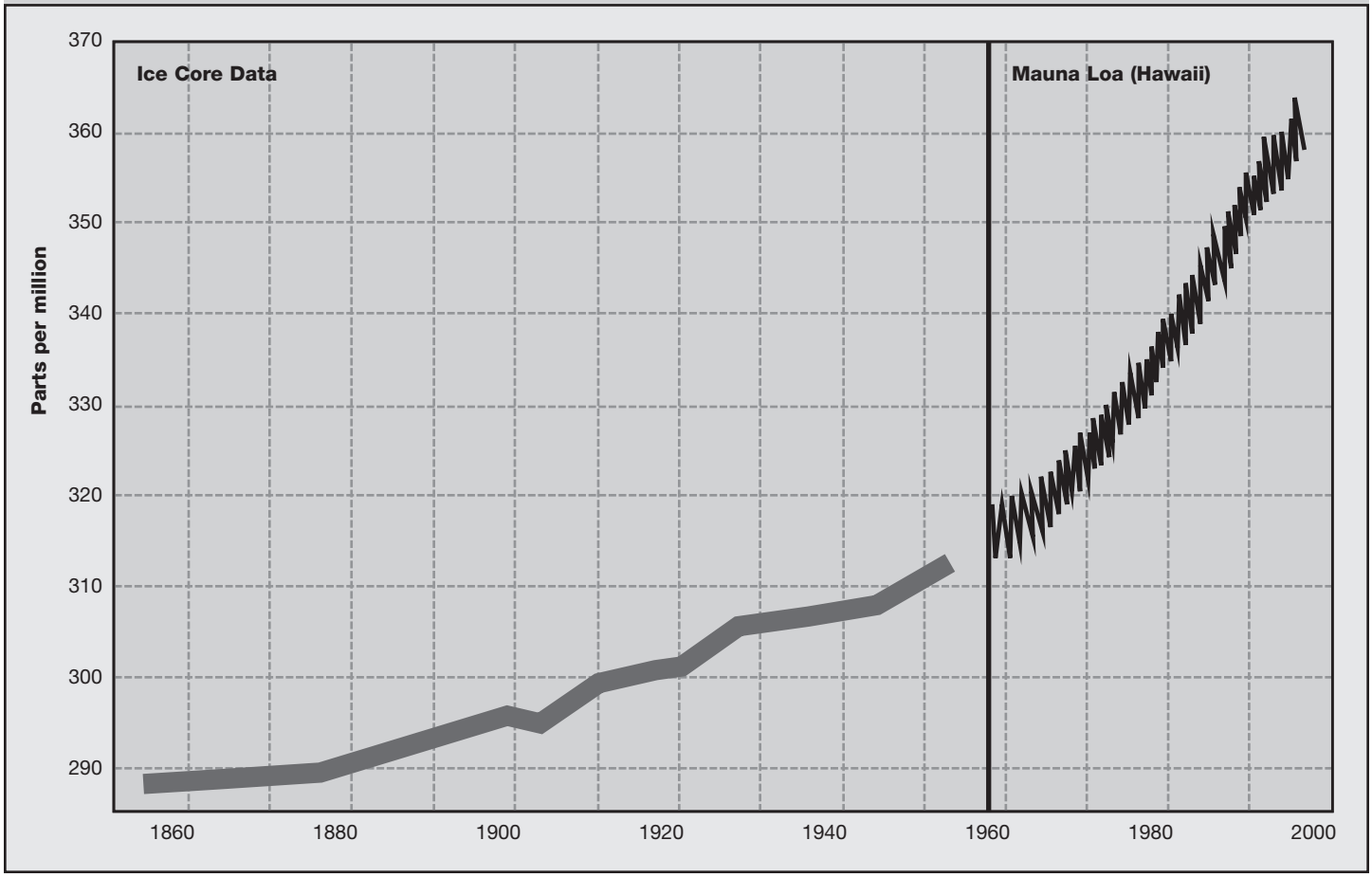
FIGURE 3.8. ATMOSPHERIC CONCENTRATIONS OF CARBON DIOXIDE, 1850–1995



Source: OSTP, 1997.

residence time in the atmosphere of carbon dioxide contributed by human activities, relative to the processes that remove it, is more than 100 years.

Measurements and analyses over the past 20 years have revealed that the atmospheric concentrations of two other naturally occurring greenhouse gases—methane (CH_4) and nitrous oxide (N_2O)—have increased by 145 percent and 14 percent since pre-industrial times. Apparently these increases are at least partly due to direct inputs from human activities as well as to alteration of ecological conditions. The wholly anthropogenic chlorofluorocarbons (CFCs) implicated in the depletion of stratospheric ozone are potent greenhouse gases as well. The warming effect of ozone, itself a greenhouse gas, has been increased in the troposphere (as a result of anthropogenic emissions of hydrocarbons and nitrogen oxides) by more than CFCs have decreased it in the stratosphere.

Changes in the atmospheric concentrations of methane, nitrous oxide, chlorofluorocarbons, and ozone since pre-industrial times are thought to have increased by about 75 percent the warming potential that would be expected from the observed increases in carbon dioxide concentrations alone. Increases over this same period in the atmospheric concentrations of particulate matter produced by combustion of fossil fuels and biomass have offset part of the warming effect of the greenhouse gas increases.[14] This offset, for which the best estimate is about half of the overall warming effect

TABLE 3.4. SOURCES AND FATES OF ANTHROPOGENIC CARBON EMISSIONS, 1980S

Source	Billions of tonnes of contained carbon
Emissions from fossil-fuel combustion and cement production	5.5 ± 0.5
Emissions from tropical deforestation	1.6 ± 1.0
Total anthropogenic emissions	7.1 ± 1.1
Fate	
Storage in the atmosphere	3.3 ± 0.2
Uptake by the oceans	2.0 ± 0.8
Uptake by terrestrial ecosystems	1.8 ± 1.6

Source: IPCC, 1996.

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TABLE 3.5. CHANGES IN EARTH'S ENERGY BALANCE, PRE-INDUSTRIAL TIMES–1992

Effect	Global average watts per square metre
Direct effect of increasing carbon dioxide	1.6 ± 0.2
Direct effect of increasing methane	0.5 ± 0.1
Direct effect of increasing halocarbons	0.25 ± 0.04
Direct effect of increasing tropospheric ozone	0.4 ± 0.2
Direct effect of decreasing stratospheric ozone	0.1 ± 0.02
Direct effect of tropospheric aerosols	-0.5 ± 0.3
Indirect effect of tropospheric aerosols	-0.8 ± 0.8
Direct effect of natural changes in solar output (since 1850)	0.3 ± 0.1

Source: IPCC, 1996.

that would otherwise have occurred through 1995, is likely to diminish as emissions of particulates and their precursors are more tightly regulated.[15] Estimated effects of the various anthropogenic greenhouse gases on Earth's energy balance are shown in table 3.5, together with estimates of other changing influences on this balance.

Are the changes in climate being observed in the forms and magnitudes that theory predicts for the measured increases in greenhouse gases? Although natural fluctuations in climatic variables would tend to mask human-caused disruption in its early stages, a variety of evidence indicates that the 'signal' of anthropogenic change is becoming visible despite the 'noise' of these fluctuations. Specifically:

- Near-surface air temperatures around the globe have increased by 0.3–0.6 degrees Celsius since the late 19th century.[16] The 11 hottest years since 1860 have all occurred since 1983 (notwithstanding the multiyear cooling effect of particulate matter injected into the stratosphere by a major volcanic eruption in 1991).
- Directly measured ocean surface-water temperatures have also increased by 0.3–0.6 degrees Celsius on a global average over the past century. In the same period the global sea level, as determined from tidal-range measurements, rose 10–25 centimetres (4–10 inches). Mountain glaciers have generally been in retreat all over the world, and mid- to-high-latitude cloudiness and precipitation have generally been increasing.

These observed changes in climatic variables are consistent, in overall magnitudes and in the general pattern of their geographic distribution, with the predictions of basic theory for the effects of the changes in greenhouse gas and particulate matter concentrations known to have occurred over this period.

The observed climatic changes are also similar to the predictions of the most sophisticated computer models of global climate, when these models include the observed build-up of greenhouse gases (corrected for the effect of atmospheric particulate matter).[17] This agreement among theory, observation, and computer modelling extends, moreover, to a variety of subtler trends for which reliable measurements have become available only for the past 15–25 years, such as cooling in the lower stratosphere, reduction of day-night temperature differences, and maximum surface warming in northern high latitudes in winter. Taken together, these phenomena are 'fingerprints' of greenhouse gas–induced climate change—consistent with the hypothesis that increases in those gases explain the observed changes, and inconsistent with alternative hypotheses.

Based on the evidence and arguments summarised here, the Intergovernmental Panel on Climate Change (IPCC) concluded in its Second Assessment that "the balance of evidence suggests a discernible human influence on climate" (IPCC, 1996b, p. 4). In that report the IPCC also extended its earlier analyses of how the human influence on climate would be expected to grow under a 'business as usual' trajectory of future greenhouse gas emissions and under higher and lower trajectories. The panel found that, under the range of trajectories considered (and taking into account the uncertainty in the global temperature response to a given increase in greenhouse gas concentrations), the global average surface air temperature would be 1.0–3.5 degrees Celsius higher in 2100 than in 1990.[18]

In all these cases, according to the IPCC (1996b, p. 5), the average rate of warming in the 21st century "would probably be greater than any seen in the last 10,000 years." In the IPCC's 'business as usual' emissions scenario, the average global temperature increase between 1990 and 2100 is 2.0 degrees Celsius—about 2.5 degrees Celsius above the temperature a century ago—which would make the world warmer than it has been at any time in the last 125,000 years. In this scenario the sea level would rise 50 centimetres between 1990 and 2100, then "continue to rise at a similar rate in future centuries beyond 2100, even if concentrations of greenhouse gases were stabilized by that time, and would continue to do so even beyond the time of stabilization of global mean temperature" (IPCC, 1996b. p. 5).

The IPCC assessment gives due consideration attention to the range of possible outcomes and to the size of the uncertainties attached to the group's best estimates. Still, the range of expected ecological and social impacts of climate changes in the next century leave little room for complacency even at the lower end of the range. And the uncertainties include the possibility of unpleasant surprises that would extend the upper end:

> Further unexpected, large and rapid climate system changes (as have occurred in the past) are, by their nature, difficult to predict. This implies that future climate changes may also involve "surprises". In particular these arise from the non-linear nature of the climate system. When rapidly forced, non-linear systems are especially subject to unexpected behavior. Progress can be made by investigating non-linear processes and subcomponents of the climate system. Examples of such non-linear behavior include rapid circulation

Mountain glaciers have generally been in retreat all over the world.

changes in the North Atlantic and feedbacks associated with terrestrial ecosystem changes. (IPCC, 1996b, p. 6)[19]

Since the IPCC's Second Assessment, scientific evidence has continued to accumulate concerning human influences on the global climate system.[20] In particular, the data and analyses show more compellingly than ever that Earth's average surface temperature is increasing and that this increase can largely be attributed to the accumulation of greenhouse gases in the atmosphere caused by human activities. Among the recent findings:

- *1998 appears to have been the warmest year in a millennium,* and the 1990s were the warmest decade in 1,000 years for the Northern hemisphere. Scientists have reconstructed the millennial temperature record in the Northern hemisphere using proxy data for temperatures, such as ice cores, lake sediments, corals, and tree rings (Mann, Bradley, and Hughes, 1999).
- *Greenhouse gases from human activities are the driver of these temperature increases.* While solar variability, volcanic eruptions, and El Niño cycles also contribute to these global temperature patterns, the 20th century record cannot be explained solely by invoking these phenomena (Mann, Bradley, and Hughes, 1998).
- *Regional patterns of temperature change across Earth's surface and vertical patterns of temperature change in the atmosphere provide further evidence of human-induced global warming.* These patterns are consistent with what is expected under anthropogenic climate change—and are inconsistent with hypotheses that suggest that solar variability or the urban-heat island effect can be used to explain the instrumental temperature record (see Wigley, Smith, and Santer, 1998; Wentz and Schabel, 1998; and Peterson and others, 1999).

Consequences of greenhouse gas–induced climate change

There is a natural tendency to suppose that an average global warming of 2.5 degrees Celsius—around the mid-range projection for the year 2100 relative to 1900—would not be such a bad thing. Raising Earth's average surface temperature from 15.0 to 17.5 degrees Celsius (from 59.0 to 63.5 degrees Fahrenheit) does not, at first glance, seem to be especially problematic. Some regions would have longer growing seasons, and some would have shorter seasons of freezing weather. What would be so bad about that?

Such complacency is unwarranted for several reasons. Most important, small changes in the average global surface temperature will cause many changes in other climatic variables—latitudinal temperature differences, frequency of extreme temperatures, atmospheric circulation patterns, precipitation patterns, humidity, soil moisture, ocean currents, and more—that affect human well-being in myriad ways. Climatic conditions are the 'envelope' in which all other environmental conditions and processes exist and operate. Thus climate exerts powerful influences over, for example, the productivity of farms, forests, and fisheries, the geography of human disease, and the abundance and distribution of the plants, animals, and microorganisms constituting biodiversity, as well as determines the availability of water, the frequency and intensity of damage from storms and floods, the combination of heat and humidity that determines liveability (and requirements for air conditioning) in warm regions in summer, and the potential property loss from rising sea level.

The average global surface temperature, then, is not a number that by itself reveals the features of climate that matter most—the spatial and temporal patterns of hot and cold, wet and dry, wind and calm, frost and thaw that constitute the climate locally and regionally, where people live. Rather, it is a single, highly aggregated index of the global climatic state that is correlated in complicated ways with those crucial local and regional climatic features. When the average global temperature increases, the regional increases will be greater on land than on the ocean surface, greater inland than near the coasts, and greater at high latitudes than near the equator. In mid-latitude, mid-continent regions—the midwestern United States, for example—the increase in average temperature is expected to be 1.3–2.0 times the average global increase (hence as much as a 5 degree Celsius increase when the global average has gone up by 2.5 degrees; Wigley, 1999 and IPCC, 1996b). At higher latitudes—central Canada, northern Russia—the increase could be three times the global average, or more.

Evaporation and, hence, precipitation are expected to increase about 3 percent for each 1 degree Celsius increase in the average global temperature. (Thus a 2.5 degree Celsius increase in the average global temperature would produce a 7.5 percent increase in precipitation.) In addition, a larger fraction of the precipitation is expected to occur during extreme precipitation events, leading to an increase in flooding.[21] Notwithstanding the increase in precipitation, the increase in evaporation will likely reduce summer soil moisture over large regions, increasing the frequency and severity of droughts in some. At the same time, humid regions will likely become more so. Climate simulations conducted at the Geophysical Fluid Dynamics Laboratory of the U.S. National Oceanographic and Atmospheric Administration show that the average heat index (a discomfort indicator combining temperature and humidity) for the southeastern United States in July will increase from about 30 degrees Celsius (86 degrees Fahrenheit) today to about 35 degrees Celsius (95 degrees Fahrenheit) by the time the average global surface temperature has increased 2.5 degrees Celsius (GFDL, 1997).

As the average temperature and average heat index go up, the frequency of days with extremely high temperature and humidity increases disproportionately. An average warming of 1 degree Celsius might increase the number of days over a particular threshold by 10 percent, while a 2 degree Celsius increase would increase the number of days over that threshold by substantially more than 20 percent (Wigley, 1999; IPCC, 1996b). This result portends not only much

> In a range of cases considered by the IPCC, the average rate of warming in the 21st century "would probably be greater than any seen in the last 10,000 years."

higher summer discomfort in a greenhouse gas–warmed climate but also a possibility of substantial increases in death rates from heat stress in areas that are already hot and humid in summer. A decrease in cold-related deaths in winter would partly offset this effect, but for a variety of reasons seems unlikely to offset it entirely (IPCC, 1996a).

An increase in sea level at the mid-range value of 50 centimetres between 1990 and 2100 would be devastating to low-lying islands and seriously damaging to coastal wetlands and many coastal communities. As with temperature, the damage will come not just from the increase in the average but from the increase in extremes. In the case of sea level, this refers to the damage done by storm surges and storm waves starting from a higher baseline (IPCC, 1996a).

As for the frequency and intensity of damaging storms themselves—hurricanes and typhoons in particular—some lines of argument and evidence suggest increases in a greenhouse gas–warmed world, but the origins and dynamics of such storms are complicated. The higher sea surface temperatures and higher atmospheric moisture contents associated with a warmer world tend to produce more powerful storms, all else being equal, but other relevant factors that could be affected by climate change might offset this tendency. There is evidence of an increase in the frequency of Atlantic hurricanes based on a correlation with sea surface temperatures, and there are simulation results indicating higher wind speeds and lower pressures in tropical storms world-wide under global temperature increases in the range expected for the 21st century (see Wigley, 1999 and Knutson, Tuleya, and Kurihara, 1998).

Also subject to considerable uncertainty are the effects of global warming on the large-scale patterns of atmospheric and oceanic circulation that are so crucial in determining regional climates. One thinks particularly of the El Niño/Southern Oscillation phenomenon that affects climates across the central Pacific and the Americas and all the way to Africa, the monsoons that are so critical across Africa and South Asia, and the North Atlantic thermohaline circulation that drives the Gulf Stream and greatly moderates the winter climate in Western and Northern Europe. Although there is every reason to expect that global warming would influence these phenomena, neither historical correlations nor the ocean-atmosphere models used to simulate global climate have proven adequate for predicting with confidence what the exact effects will be.

There are, however, some suggestive preliminary findings. Some modelling results, for example, indicate a substantial weakening of the North Atlantic thermohaline circulation from greenhouse gas–induced warming, setting in well before the pre-industrial carbon dioxide concentration has doubled (Broecker, 1997; GFDL, 1997). Such a weakening would, somewhat paradoxically, make Europe much colder in winter in a world that was warmer overall.

And even bigger changes, such as some that might ensue from ocean-atmosphere-ice interactions, cannot be ruled out. One such scenario involves the complete melting of the Arctic sea ice (with no effect on sea level, since floating ice displaces its weight in water, but with large potential effects on oceanic and atmospheric circulations). Another involves the collapse of the largely land-borne but ocean-anchored West Antarctic Ice Sheet, the slow slide of which into the ocean if the anchor points melted away could raise sea level by 5 metres in 500 years (Oppenheimer, 1998).

If the ways in which global warming will affect regional climates are uncertain, the ecological consequences of those regional changes are even more so. Certainly both the averages and extremes of temperature, humidity, and precipitation are critical in governing the distribution and abundance of terrestrial animals, plants, and microorganisms, just as the averages and extremes of ocean temperatures, salinities, and current patterns are critical to marine life. The organisms in question include, of course, the plants that are the foundation of all terrestrial and oceanic food chains—including all those that support the human population—and they include the pests and pathogens that can destroy crops, fell farm animals, ravage forests, and bring debilitating diseases to humans. Even without the capacity to predict specific effects in detail (which is lacking because of inadequacies in ecological as well as climatological understanding), it is worth noting that:

- The conditions governing what grows where on land are generally the result of co-evolution of soils, vegetation, and climate. Adjusting to climate change is therefore not just a matter of allowing cropping patterns and forest characteristics to rapidly migrate to a rearranged set of climatic zones; reaching a new equilibrium could take centuries. And where drastic changes in agricultural practices are required to deal with climate change, the capital- and infrastructure-poor developing world will be differentially disadvantaged.
- Winter is the best pesticide (which is why crop pests and many disease vectors and pathogens are more problematic in the tropics than in temperate zones). This means that warmer winters outside the tropics will be problematic for food production and for human disease.
- The warmer, wetter conditions that global warming will bring to many of the world's temperate zones will expand the ranges of a variety of diseases (including, quite probably, malaria, cholera, and dengue fever). Industrialised countries' technological and biomedical defences against these diseases may prove less robust than optimists predict, not least because of the continuing emergence of drug-resistant strains.

The conclusions of the IPCC Second Assessment about the consequences of the greenhouse gas–induced warming expected over the 21st century include the following (IPCC, 1996a):

- Agricultural productivity "is projected to increase in some areas and decrease in others, especially the tropics and subtropics."[22] "Low-income populations depending on isolated agricultural systems, particularly dryland systems in semi-arid and arid regions,

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are particularly vulnerable to hunger and severe hardship" (p. 6).

- "As a consequence of possible changes in temperature and water availability under doubled equivalent of CO_2 equilibrium conditions, a substantial fraction (a global average of one third, varying by region from one seventh to two thirds) of the existing forested area of the world will undergo major changes in broad vegetation types—with the greatest changes occurring in high latitudes and the least in the tropics" (pp. 5–6).
- "Climate change is likely to have wide-ranging and mostly adverse impacts on human health, with significant loss of life…Net climate-change-related increases in the geographic distribution (altitude and latitude) of the vector organisms of infectious diseases (e.g., malarial mosquitoes, schistosome-spreading snails) and changes in the life-cycle dynamics of both vector and infective parasites would, in aggregate, increase the potential transmission of many vector-borne diseases…Increases in non-vector-borne infectious diseases such as cholera, salmonellosis, and other food- and water-related infections also could occur, particularly in tropical and subtropical regions, because of climatic impacts on water distribution, temperature, and microorganism proliferation… [H]otter temperatures in urban environments would enhance both the formation of secondary pollutants (e.g., ozone) and the health impact of certain air pollutants. There would be increases in the frequency of allergic disorders and of cardiorespiratory disorders and deaths caused by various air pollutants."
- "Climate change and the resulting sea-level rise can have a number of negative impacts on energy, industry, and transportation infrastructure; human settlements; the property insurance industry; tourism; and cultural systems and values."

Nearly all attempts to predict the consequences of greenhouse gas–induced climate change, including those of the IPCC, have confined themselves to addressing the changes associated with roughly a doubling of pre-industrial carbon dioxide concentrations. This has been done so that the results of studies by different investigators would be readily comparable, inasmuch as they were all looking at a similar degree of climate change—not because there is any particular reason to believe that no more than a doubling of pre-industrial carbon dioxide will occur. Indeed, as the next section indicates, the world could end up with carbon dioxide levels three or even four times the pre-industrial value. But the prevalence of studies that look only at the effects of a doubling seems to have led many people to suppose that these are the most that could occur.

In reality, as the few studies of higher levels of warming make plain, the uncertainties and controversies surrounding whether a doubling of atmospheric carbon dioxide would have overwhelmingly negative consequences are of much less importance when one contemplates a quadrupling. A study of quadrupling by one of the main U.S. climate study centres concluded, for example, that the average temperature increases in Northern hemisphere mid-continent regions would be 8–12 degrees Celsius (15–22 degrees Fahrenheit), that mid-continent soil moisture in summer would fall about 50 percent from 1990s levels; that the sea level rise from thermal expansion alone (not allowing for the melting of any of the Greenland or Antarctic ice sheets) would approach 2 metres; that the North Atlantic thermohaline circulation would shut down completely; and that the July heat index for the southeastern United States would reach 44 degrees Celsius (110 degrees Fahrenheit). The ecological consequences of such changes—and their influence on humans—would be immense.

Greenhouse gas–induced climate change could also affect energy systems, potentially influencing their cost and reliability. The attractiveness of hydropower, windpower, and biomass energy systems, for example, depends on favourable and stable, or at least predictable, climate conditions at their sites over decades. Energy demand is also a function of climate, and changes in temperature, precipitation, wind, and the like will affect it. Thus it is conceivable that climate-change–related reductions in the attractiveness of renewables combined with increases in energy demand could act as positive feedback mechanisms—increasing greenhouse gas emissions faster than they would otherwise because of greater use of fossil fuels.

Alternative energy futures and greenhouse gas emissions

According to the IPCC, in 1990 global emissions of carbon dioxide from fossil fuel burning totalled about 5.9 billion tonnes of contained carbon. (It is customary to keep track of carbon dioxide emissions in terms of their carbon content rather than their total mass, to facilitate comparisons with other stocks and flows in the global carbon cycle in which carbon may be in a variety of chemical compounds.) Carbon dioxide emissions from tropical deforestation totalled about 1.5 billion tonnes, with an uncertainty of plus or minus 1.0 billion tonnes. The IPCC assumes that rates of tropical deforestation will decline in the 21st century, becoming even smaller relative to fossil fuel carbon dioxide emissions. In 1997 fossil fuel combustion produced about 6.3 billion tonnes of carbon emissions (table 3.6).

The geographic distribution of industrial emissions of carbon—that is, emissions from fossil fuel combustion (including flaring of

TABLE 3.6 SOURCES OF INDUSTRIAL CARBON EMISSIONS, 1997 (BILLIONS OF TONNES)

Combustion of petroleum products	2.70
Combustion of coal	2.40
Combustion of natural gas for energy use	1.20
Cement manufacturing	0.20
Flaring of natural gas	0.05
Total	**6.60**

Source: Authors' calculations based on energy data from BP, 1998 and USEIA, 1998.

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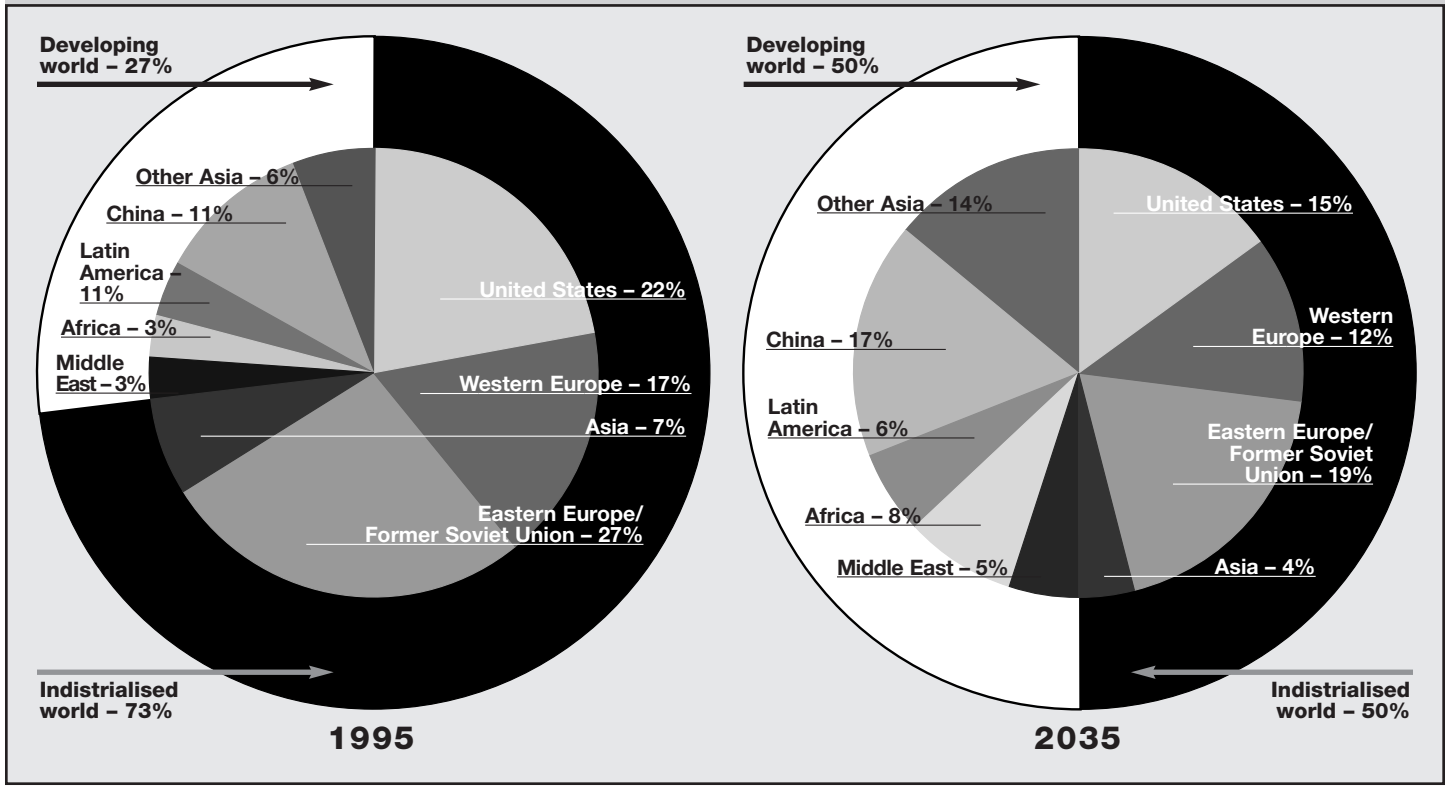
FIGURE 3.9. SOURCES OF INDUSTRIAL CARBON DIOXIDE EMISSIONS, 1995 AND 2035



Source: OSTP, 1997.

natural gas) and cement manufacturing—is shown in figure 3.9 for 1995 and projects for 2035 under a 'business as usual' energy future. In 1995 nearly three-quarters of these emissions came from industrialised countries. Under the business as usual scenario, the developing country share will equal that of industrialised countries by 2035. (The cumulative contribution of developing countries to the atmospheric burden of anthropogenic carbon dioxide will remain smaller than that of industrialised countries for some time thereafter, however, and per capita emissions from developing countries will remain smaller than those from industrialised ones for longer still.)

The IPCC analysis and its scenarios for future emissions also take into account the other anthropogenic greenhouse gases—methane, tropospheric ozone, nitrous oxide, and halocarbons—and anthropogenic particulate matter in the atmosphere that partly offsets the heat-trapping effect of the greenhouse gases by screening out incoming sunlight. As noted, the IPCC found that, as of the mid-1990s, the non–carbon dioxide greenhouse gases had added about 75 percent to the heat-trapping effect that would have resulted from the build-up of carbon dioxide alone. But the IPCC's best estimate of the effect of increasing particle concentrations was that these had approximately cancelled out the effect of the increases in non–carbon dioxide greenhouse gases. In one of the six scenarios developed by the IPCC in 1992, the 'central' scenario designated IS92a, increases in the effects of atmospheric particles over the next 100 years continue to roughly counterbalance the effects of increases in the non–carbon dioxide greenhouse gases. Thus the net increase in the heat-trapping effect over this period is about what would be expected from the carbon dioxide build-up alone.

The IS92a scenario is very similar to the 'unsustainable' IIASA-WEC (International Institute for Applied Systems Analysis–World Energy Council) A2 scenario presented in chapter 2. Both are based on World Bank 'medium' population projections; the IS92a scenario uses an older median projection in which the world population reaches 11.3 billion by 2100 and the IIASA-WEC uses a newer projection of 10.7 billion by 2100. The IS92a scenario assumes that real economic growth world-wide averages 2.9 percent a year from 1990 to 2025 and 2.0 percent a year from 2025 to 2100, resulting in overall growth of 2.3 percent a year from 1990–2100 compared with 2.5 percent a year in the A2 scenario. Both scenarios assume that the energy intensity of economic activity (energy per unit of real GDP) declines by 1.0 percent a year from 1990–2100 and that the carbon intensity of energy supply (kilograms of carbon emitted in carbon dioxide per unit of energy supplied) decreases by 0.2 percent a year over this period. The result is that global carbon emissions increase in both scenarios from 7.4 billion tonnes a year in 1990 to 20.0 billion tonnes a year in 2100, and cumulative carbon emissions between 1990 and 2100 total 1,500 billion tonnes.

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The carbon content of the atmosphere in 2100 under the IS92a and A2 scenarios would be some 1,500 billion tonnes, or about 715 parts per million of carbon dioxide by volume, 2.5 times the pre-industrial level, and still rising steeply. (Only about half of the 1,500 billion tonnes of carbon added between 1990 and 2100 would have remained in the atmosphere, the rest having been taken up by oceans and by vegetation according to the IPCC's carbon cycle model.) This is the scenario for which the IPCC obtained the surface temperature and sea level estimates mentioned above. Because of the thermal lag time of the oceans and the continuing melting of polar ice under warmer conditions, both temperature and sea level would continue to rise after 2100 even if the growth of atmospheric carbon dioxide were halted at that point.

The challenge of stabilising the carbon dioxide content of the atmosphere is illustrated in the IPCC's Second Assessment with emission trajectories that would be able to achieve stabilisation at concentrations ranging from 450–1,000 parts per million by volume (ppmv). (The pre-industrial concentration was about 280 ppmv; today's is 365 ppmv.) These trajectories can be characterised by the cumulative and average emissions they entail between 1990 and 2100 (although what happens after that also matters). The results are summarised in table 3.7.

The IPCC's IS92a scenario and the IIASA-WEC A2 scenario, with cumulative emissions of 1,500 billion tonnes of carbon between 1990 and 2100 and annual emissions of 20 billion tonnes of carbon in 2100, are both above even the highest of these stabilisation trajectories. Such emissions would nearly triple pre-industrial atmospheric carbon content by 2100 and create a situation in which an eventual quadrupling or more could not be avoided no matter what measures were taken thereafter. (These levels are so high as to render irrelevant the current controversies over exactly how severe the climatic consequences of a doubling of atmospheric carbon might be; a quadrupling would transform Earth's climate beyond recognition; see GFDL, 1997.)

To illustrate the challenge associated with reducing emissions to the levels being debated in the context of the United Nations Framework Convention on Climate Change (UNFCCC), consider what the numbers above imply for the stabilisation target for atmospheric carbon dioxide of 550 ppmv, about twice the pre-industrial level. (While there can be no confidence that this level would avoid climate change seriously disruptive of human well-being throughout much of the world, a doubled carbon dioxide target is widely discussed because it is, at least arguably, near the upper limit of what is tolerable and near the lower limit of what seems achievable.) This would require that cumulative emissions between 1990 and 2100 be less than two-thirds those in the IS92a scenario. It would also require that emissions begin to decline after peaking at about 11 billion tonnes of carbon a year around 2030.

This more sustainable development path and the challenge of achieving the transition towards such a path are illustrated by the IIASA-WEC C scenario presented in chapter 9. That scenario leads to the stabilisation of atmospheric carbon concentrations at about 430 ppmv and cumulative emissions of some 540 billion tonnes of carbon from 1990–2100. Perhaps more important, the development path that leads to atmospheric stabilisation of carbon at a relatively benign level also leads to the fulfilment of most of the other criteria for sustainable development discussed in this report.

The difficulty of achieving this goal becomes particularly apparent when one views it in terms of the roles of industrialised and developing countries. In 1990 industrialised countries emitted about 4.5 billion tonnes of carbon from fossil fuel burning (three-quarters of the world total, or 3.6 tonnes per inhabitant of these countries). Developing countries emitted 1.5 billion tonnes (about 0.37 tonnes per capita). In 1992, as part of the UNFCC, industrialised countries agreed to try to limit their carbon emissions in 2000 to 1990 levels (see below). But few are on a track towards achieving this. For example, in 1997 U.S. carbon emissions were about 9 percent higher than in 1990.

Considerably more effort is required. For example, assume that industrialised countries were willing and able to return to their 1990 carbon emissions by 2010—a decade after the initial UNFCCC target (and a performance considerably weaker than called for in the 1997 Kyoto Protocol; see below)—and were also willing and able to reduce these levels by 10 percent a decade thereafter. Even then, stabilising atmospheric carbon dioxide concentrations at 550 ppmv would still require that per capita emissions in developing

TABLE 3.7. IPCC SCENARIOS FOR STABILISING CARBON DIOXIDE LEVELS, 2075–2375

To stabilise concentrations at (parts per million by volume)	450	550	650	750	1,000
By about the year	2075	2125	2175	2200	2375
Cumulative emissions in 1990–2100 would need to be in the range of (billions of tonnes of carbon)	550–750	750–1,100	970–1,270	1,090–1,430	1,220–1,610
Average emissions in 1990–2100 would be in the range of (billions of tonnes of carbon per year)	5.7–5.9	7.9–9.0	10.2–10.8	10.0–11.8	12.7
And peak emissions (billions of tonnes of carbon per year)	9.5	11	12.5	13.5	15
In the year	2012	2030	2050	2060	2075

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countries not exceed 1 tonne of carbon in the global peak-emissions year of 2030. (This assumes that emissions from deforestation have been eliminated by 2030 and that the population of developing countries is about 7.5 billion at that time, consistent with the 'medium' World Bank projection.) As shown in later chapters, with vigorous promotion of renewables and energy-efficient technologies, such a per capita level could produce much higher living standards.

Even more challenging, given the justifiable economic aspirations of developing countries, the unwillingness of many industrialised countries to take the steps needed to reduce emissions, and the common expectations of all countries to rely heavily on expanded fossil fuel use, is that the per capita emissions of both industrialised and developing countries would need to fall sharply after 2030 to stay on this 550 ppmv stabilisation trajectory. (See chapter 9 for more discussion of carbon emission scenarios, particularly the C scenario, which achieves the required emissions reduction discussed here.)

International agreements to address global climate change

The UNFCCC is the first binding international legal instrument that deals directly with the threat of climate change. Since its enactment at the 1992 'Earth Summit' in Rio de Janeiro, the convention has been signed by more than 165 states (plus the European Union). It came into force in March 1994.

Signatory countries agreed to take action to realise the goal outlined in article 2 of the convention, namely the "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system." To achieve this, all parties to the convention, both industrialised and developing, are committed under article 4 to adopt national programs for mitigating climate change; to promote the sustainable management and conservation of greenhouse gas 'sinks' (such as forests); to develop adaptation strategies; to take climate change into account when setting relevant social, economic, and environmental policies; to cooperate in technical, scientific,

BOX 3.7. GREENHOUSE GASES AND NATURAL DEBT

Countries take on national debt when they spend money faster than their economies produce it. Building up national debt is e ssentially a way of borrowing from the country's future earnings. A little national debt can be beneficial, by providing resources so that the economy grows faster than it otherwise might. But a lot of national debt can be quite disruptive. Countries can also take on 'natural debt' by putting pollutants into the environment faster than they are naturally removed. In this way they borrow from the environment's future assimilative capacity.

Humanity has been adding greenhouse gases to the atmosphere faster than they can be naturally removed. As a result the global atmospheric burden of carbon dioxide and other greenhouse gases has been rising. The extra burden of greenhouse gases in the atmosphere above pre-industrial levels is a measure of the global natural debt. Indeed, this natural greenhouse gas debt is the principal driver of climate change, since it determines the extra radiative forcing (warming).

Although most discussions of greenhouse gas control address the current emissions of countries, cumulative emissions (natural debt) are the chief determinant of the impact on the climate. The natural debts of countries differ substantially more than do current emissions, because some countries have been emitting large amounts for much longer than others have. The largest natural debts have been accrued by industrialised countries, which started burning large amounts of fossil fuels early in the 20th century. Some of those greenhouse gases have been removed naturally from the atmosphere, but some remain because of long residence times. The table below compares the natural debts of a number of countries that together account for 55 percent of the world's population and about 75 percent of global carbon dioxide emissions.

It has been argued that it would be more appropriate to determine a country's responsibility for reducing emissions based on its natural debt relative to that of other countries rather than on current emissions, since natural debt (cumulative greenhouse gases in the atmosphere) is more closely related to actual climate impact. Such proposals are not welcomed by negotiators for most industrialised countries.

One argument against using natural debt as a measure of responsibility is that it would be unfair. After all, it is argued, the ancestors of today's populations in industrialised countries did not know they were causing a problem by emitting greenhouse gases. Thus today's populations, who did not do the polluting, should not have to pay for past mistakes. This view is partly accounted for in the table above, which only measures emissions from 1950. But there are two important counter-arguments:

- Today's rich populations have enjoyed the (considerable) benefits derived from past use of fossil fuels and other greenhouse gas–generating activities and thus should accept the debts that go along with those benefits. It is not a matter of punishment, but one of recognising the debits as well as the credits (the polluter pays principle).
- Saying that if someone did not know they were doing a risky thing that they need not be held responsible is a sure way to encourage people not to make the effort to discover whether their activities might cause problems for future generations. It essentially rewards ignorance. A sustainable world energy system, on the other hand, is one in which cross-generational responsibility is accepted by all.

Box table. Natural debt: Carbon as carbon dioxide remaining in the global atmosphere from fossil fuel combustion

	Current emissions 1996 (tonnes per capita)	Cumulative emissions 1950–96 (tonnes per capita)
United States	5.3	119
Canada	4.2	91
Germany	3.3	87
Russia	3.9	78
United Kingdom	2.7	78
Australia	4.1	70
Sweden	1.7	54
France	1.8	49
Japan	2.4	41
Korea, Dem. Rep.	3.0	32
Korea, Rep.	1.7	16
China	0.6	8
India	0.2	3

Source: Smith, 1991a; Hayes and Smith, 1994; Smith, 1997.

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Climate change is likely to have wide-ranging and mostly adverse impacts on human health, with significant loss of life.

and educational matters; and to promote scientific research and information exchange.

The UNFCCC also establishes more demanding obligations for industrialised countries, which agreed to try to reduce emissions of carbon dioxide and other greenhouse gases to 1990 levels by 2000. OECD countries are also committed to facilitating the transfer of financial and technological resources to developing countries, beyond those already available through existing development assistance. The convention requires industrialised countries to take the lead in adopting measures to combat climate change, recognising that they are mainly responsible for historic and current emissions of greenhouse gases, and that developing countries will need assistance to meet the treaty's obligations.

The structure provided by the UNFCCC is being built on with additions agreed in a series of conferences of the parties. Most notably:

- The first conference of the parties, held in Berlin (Germany) in March 1995, focused on the need to reinforce the commitments in article 4 of the UNFCCC with "quantified limitation and reduction" objectives for annex 1 countries after 2000.[24] The mandate did not call for new commitments for developing country parties but only for enhanced efforts at implementing the existing commitments relating to these countries in article 4.
- The third conference of the parties, held in Kyoto (Japan) in December 1997, produced a protocol to the framework convention codifying commitments for reductions in greenhouse gas emissions after 2000. The protocol commits annex I parties (except Australia, Iceland, New Zealand, Norway, Russia, and Ukraine) to reduce greenhouse gas emissions by 5–8 percent below 1990 levels between 2008 and 2012 and to make "demonstrable progress" towards achieving these commitments by 2005. Overall emissions are to be computed on a net basis, accounting for afforestation, reforestation, and deforestation as well as emissions from energy supply and other industrial activities. (See box 3.7 for a discussion of another approach to measuring a country's greenhouse gas contributions.)

The Kyoto Protocol, having not yet been ratified by the requisite number of nations, is not in force. It has been criticised by some (especially in the United States) as demanding too much too soon of industrialised nations while not requiring anything of developing countries. It has been criticised by others as not requiring enough of anyone, representing only a small 'down payment' on the kinds of emission reductions that will be required over the 21st century to avoid intolerable climate change from greenhouse gases.

Cross-scale impacts

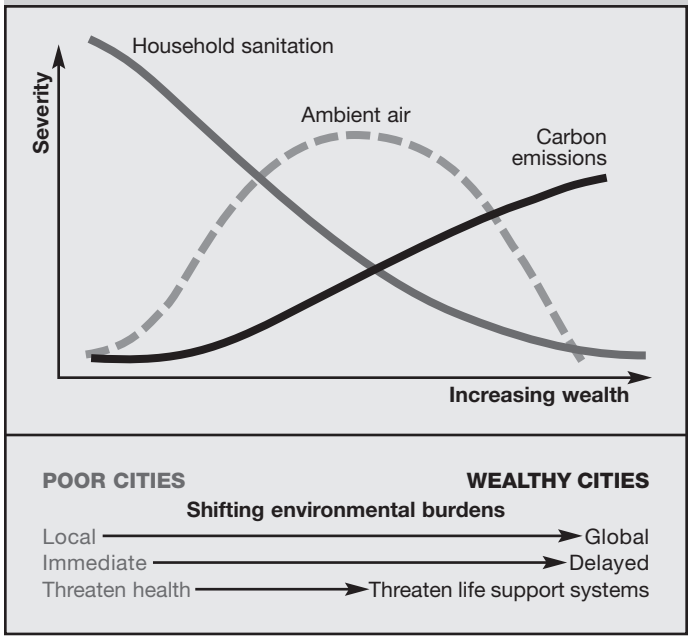
Some types of pollutants are created and create problems at every scale and easily transfer between scales. Aerosols (particulates) are a good example. At the household and community scales, they are probably the chief source of human ill health from energy systems. At the workplace scale, in the form of coal dust for example, they are a principal contributor. At the regional scale, secondary particulates from sulphur and nitrogen gases contribute to ill health and form the basis for acid deposition. At the global scale, they contribute to climate change through local warming or cooling, depending on particle composition and ground characteristics. Overall, it is believed that human-caused aerosols had a net cooling effect during the 20th century, masking some of the warming that would have occurred through greenhouse gas build-up.

The transfer of aerosols from one scale to another is governed by complicated processes involving geography, elevation, wind, moisture, size, composition, and so on. Nevertheless, in general it can be said that reducing emissions at one scale will have impacts at other scales. In most cases these benefits are beneficial. As particulates and their precursors such as sulphur oxides are brought under control because of concerns at other scales, however, greenhouse gas warming may actually be greater than in the immediate past because of their apparent net cooling effect in the atmosphere.

Environmental risk transition

During development, societies tend to push off environmental problems from smaller to larger scales (Smith, 1990, 1997). For energy, household hazards dominate fuel cycles in the poorest parts of the world, while community impacts dominate fuel cycles in middle-income cities through industrial and vehicular pollution. In the richest countries, household and community problems have mostly

FIGURE 3.10. ENVIRONMENTAL RISK TRANSITION



McGranahan and others, 2000; Smith and Akbar, 1999.

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been pushed off to the global level in the form of greenhouse gases (figure 3.10). In all countries, however, occupational risks per worker-hour tend to be much higher than risk per hour of public exposure. As with other exposures, however, occupational risks also tend to be higher in poorer countries (box 3.8).

The environmental risk transition curves in figure 3.10 should not be considered fixed in the sense that today's developing nations will be forced to go through them in the same way that today's industrialised countries have done. Rather, the curves should be viewed as a management framework by which to judge the progress of development policy. The task in developing countries is to avoid the excesses of the past, to continue to push down the household curve, and to not let the community curve rise out of hand. This might be considered a kind of 'tunnelling' through the curves to avoid climbing over the peaks by applying cleaner, more efficient energy supply and use technologies earlier in the development process than has occurred to date.

Win-win strategies to link environmental improvements at different scales

The most convincing argument for spending resources to reduce current greenhouse gas emissions is that the benefits from reduced impacts of climate change will be greater than the costs. Among the important benefits are avoiding or reducing the direct impacts on human health that might accompany climate change, and avoiding ecosystem effects that could have significant indirect impacts on humanity. Reducing current greenhouse gas emissions could generate long-term health benefits such as fewer malarial mosquitoes, fewer extreme climatic events (including tropical cyclones and heat episodes), shifts in atmospheric composition towards less pollution, reduced impacts on food production, and decreasing refugee populations from reduced sea level rise and other factors (McMichael and others, 1996). Similarly, reduced greenhouse gas emissions could lead to less damage to important ecosystems.

Each step of the causal chain from greenhouse gas emissions to global warming to direct effects on health and ecosystems is not understood with certainty, however. As a result of that uncertainty, many observers are still unconvinced that the potential but distant health and ecosystem benefits justify large spending on greenhouse gas reductions today. Although the consensus scientific opinion (as represented by the IPCC) is that such ill effects are likely if current trends in greenhouse gas emissions continue, scepticism holds back international agreements to significantly alter current greenhouse gas emissions. This is particularly so in developing countries, which must contend with many urgent problems related to human health and welfare. But it also applies to many groups in industrialised countries.

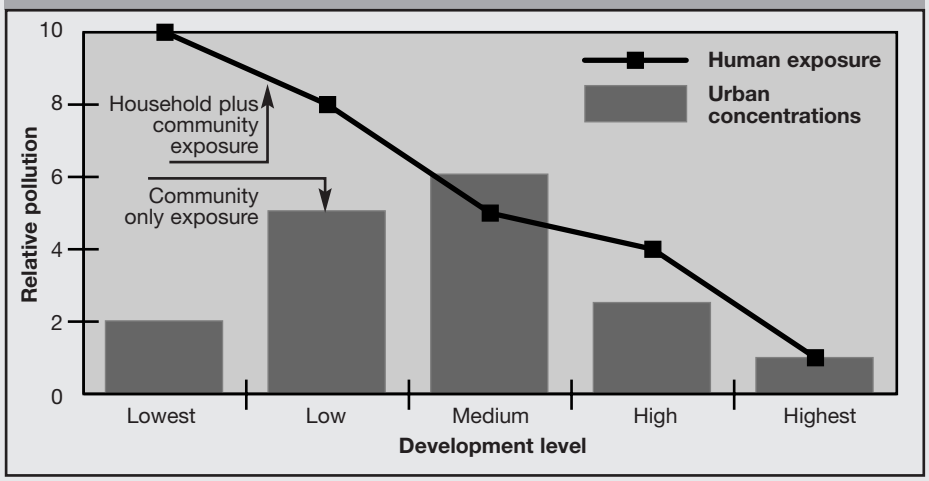
One approach to resolving this impasse is to promote 'no regrets' scenarios for reducing greenhouse gases. Such scenarios achieve significant near-term benefits for human health and ecosystems in addition to reducing greenhouse gases. Thus such immediate

BOX 3.8. THE KUZNETS ENVIRONMENTAL CURVE: FACT OR FALLACY?

An illustration of the environmental risk transition between scales is seen in the figure below, which plots the relationship between urban PM_{10} (particulates larger than 10 microns in diameter) concentrations and countries' development status as indicated by their UNDP human development index (a function of income, literacy, and life expectancy). Superficially, urban PM_{10} concentrations seem to follow the so-called Kuznets environmental curve—that is, they first rise during development, reach a peak, then decline (Grossman and Kruger, 1994). (The curve is named after the Nobel Prize–winning economist Simon Kuznets, who noted in the 1960s that many countries go through a period of increasing income inequality during development before becoming more equitable.) From the standpoint of the risk transition, however, t his curve only addresses the community scale in the form of ambient urban air pollution. It ignores what happens at other scales, which may be more important.

The main concern about particulates is their impact on human health. From a health standpoint, it is not so much urban concentrations that are critical but human exposure, which is a function of not only where the pollution is but also where the people are. Because people spend a lot of time indoors and in other places close to local sources of pollution, exposure patterns can be quite different from patterns of ambient pollution. Thus, as shown in the figure, because household sources dominant exposure in the poorest countries, the pattern of exposures is quite different than that of urban ambient concentrations. Instead of rising then falling, exposures decline continuously—illustrating that the Kuznets curve misses the actual trend, which is that overall risk tends to fall even though community risk rises, because of the shift of household to community impacts (Smith, 1993).

Box figure. Urban particulate concentrations, human exposure, and national development



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BOX 3.9. WIN-WIN CROSS-SCALE ENVIRONMENTAL STRATEGIES IN CHINA

A recent study found that greenhouse gas reductions resulting from changes in energy use would generally be accompanied by substantial near-term human health benefits in China (Wang and Smith, 1998). But the level of health benefits would vary greatly with the choice of energy technologies and sectors. Shifting from conventional coal-fired power plants to natural gas, for example, has larger health benefits than reducing global warming potential, while shifting from coal power to hydropower results in the same percentage reduction in emissions of health-damaging pollutants and greenhouse gases.

This variation in health benefits is even larger between sectors. The conservative estimates in the study show that the health benefits of a 1 tonne reduction in particulate emissions from household stoves are at least 40 times those from coal-fired power plants. In terms of human health benefits, the choice of energy technologies and sectors in which to conduct greenhouse gas reduction efforts is more important than choice of a particular target for greenhouse gas reduction.

In many developing country households the particulate emissions from burning unprocessed solid fuels (biomass and coal) routinely exceed by an order of magnitude or more the safe levels specified by the World Health Organization. Thus a 15 percent reduction by 2020 in Chinese households' greenhouse gas emissions below the 'business as usual' level would avoid more than 100,000 premature deaths a year. Reduced emissions of health-damaging pollutants through household improvements in energy efficiency and changes in the fuel mix would also reduce greenhouse gases. Thus reducing greenhouse gas emissions at the global scale would significantly ease human health impacts at the household scale.

On a national scale, a 15 percent reduction in greenhouse gases below business as usual by 2020 would result in 125,000–185,000 fewer premature deaths in both the power and household sectors, depending on different control pathways (energy efficiency or fuel substitution). This range represents about 1 percent of the total mortality in China by 2020. Other countries with high household and industrial dependence on solid fuels, such as India, could be expected to see similar benefits.

Acid deposition is increasingly serious in many regions, damaging forests, crops, and aquatic animals. The RAINS-ASIA model (Foell and others, 1995) indicates that large areas in Asia have acidity levels in excess of critical loads due to sulphur deposition, posing significant environmental threats to a variety of ecosystems. The model also projects that sulphur deposition will eventually exceed critical loads by a factor of more than 10 in many parts of Asia as a result of the growing dependence on fossil fuels. This increase will threaten the sustainability of many natural and agricultural ecosystems in the region. The model develops a series of emission control scenarios and shows that energy efficiency and fuel substitution pathways, which are also the main mitigation options for greenhouse gases, can be important instruments for controlling acid-forming emissions.

actions can be justified even if climate sensitivity to additional greenhouse gases turns out to be less than is now thought (Repetto and Austin, 1997). Examples of such near-term benefits include the environmental and energy-security advantages that would accrue through less dependence on fossil fuels, and the human welfare benefits that could emerge if an international greenhouse gas control regime were oriented towards assisting economic development and reducing vulnerability among poor populations (Hayes and Smith, 1994).

Among the significant near-term benefits of greenhouse gas reductions are the human health benefits resulting from changes in the efficiency and structure of energy use that would be a large part of most greenhouse gas reduction scenarios. Although fuel cycles have several effects on health and ecosystems—for example, through water pollution, the potential for large accidents, and occupational health and safety—the largest and most sensitive to change are probably those related to pollutant emissions from the processing and burning of fuels. The same combustion processes that produce greenhouse gas emissions such as carbon dioxide and methane also generate local and regional airborne health-damaging and acid-precursor pollutants such as particulates and sulphur oxides. Thus a reduction in greenhouse gases at the global scale, through improvements in energy efficiency and changes in the mix of fuels, can be expected to reduce health-damaging and acid-precursor pollutants as well, potentially bringing immediate environmental improvements at the household, community, and regional scales. This is a win-win strategy to link environmental improvements between scales.

The potential health benefits from reduced greenhouse gases can be estimated from the global burden of ill health from air pollution. Using airborne particulates as the indicator pollutant, the World Health Organization estimates that air pollution causes 2.7–3.0 million premature deaths a year, or 5–6 percent of global mortality (WHO, 1997). Since most of this pollution comes from the combustion of fossil and biomass fuels, which would be among the main targets of any effort to control greenhouse gases, the potential reduction in health-damaging emissions would seem to be at least as great as the target reduction in greenhouse gas emissions. Arguably it is even greater, however, since switching from dirty, less efficient fuels (such as coal) to cleaner, more efficient fuels (such as natural gas) reduces emissions of health-damaging pollutants even more than greenhouse gas emissions. With greenhouse gas reduction targets on the order of 10–20 percent, the scale of emissions of health-damaging pollutants and associated reduction of ill health could be in the same range or somewhat higher—perhaps a 250,000–750,000 annual reduction in premature deaths world-wide.

To more accurately estimate these near-term health benefits, it is necessary to link each technological option in a particular greenhouse gas reduction scenario with the accompanying reduction in emissions of health-damaging pollutants. The health impact of these emissions, however, depends on the sector of the economy in which they are taken. This is because the degree of human exposure created by a unit of emissions of health-damaging pollutants depends on where they are released relative to where people spend time, their exposure, and dose effectiveness. Thus a tonne of emissions averted in the household or transportation sectors close to where people spend much of the time will generally cause a much greater reduction in human exposure (and improvement in health) than a tonne averted in the industrial or power sectors. An example of such a

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The World Health Organization estimates that air pollution causes 2.7–3.0 million premature deaths a year, or 5–6 percent of global mortality.

win-win possibility in China is presented in box 3.9.

On a community scale, more than 1.1 billion people living in urban areas world-wide are exposed to particulate or sulphur dioxide levels in excess of World Health Organization guidelines (Schwela, 1995). These pollutants are released by industrial, household, and transportation energy use. Air pollution is particularly severe in megacities. Again, reducing greenhouse gas emissions by changing energy use and structure can also reduce the particulate and sulphur dioxide emissions that cause severe urban air pollution.

The same principle applies in the cities of the industrialised world, although the scale of absolute benefits is less because air pollution levels are lower. From an economic standpoint, however, there can still be substantial secondary benefits from greenhouse gas controls through associated reductions in health-damaging pollutants, acid precipitation, and the like. The value of these benefits could in many cases rival the costs of the greenhouse gas controls, making a true win-win result (Elkins, 1996; Burtraw and Mansur, 1999).

As noted, the near-term health and ecosystem benefits of reducing greenhouse gases provide the opportunity for a true no-regrets reduction policy in which substantial advantages accrue at various scales even if the risk of human-induced climate change turns out to be less than many people now fear. Increases in energy production and end-use efficiency and changes in the mix of fuels can reduce environmental impacts at the household, community, regional, and global scales, while meeting greenhouse gas targets. To achieve these benefits effectively, however, considerations of health and other secondary benefits should be included from the start in designing greenhouse gas control strategies.

This no-regrets strategy also has important implications for emissions trading in the form, for example, of joint implementation and clean development mechanisms. Because the near-term health improvements are local, they accrue almost entirely to the nation in which greenhouse gas control projects are undertaken—unlike the benefits of greenhouse gas reductions, which accrue globally. These large local benefits may provide a significant extra incentive for China and other developing countries to enter into arrangements in which local greenhouse gas controls are financed externally and the emission credits are shared. Indeed, a greenhouse gas reduction strategy can be consistent with such critical national development objectives as reducing local air pollution, increasing energy efficiency, and improving social equity by providing energy services to remote areas through renewable energy.

Assessment methods

A number of methods have been developed to compare the disparate effects of energy systems on a common basis. Here we discuss perhaps the two most common, economic valuation and fuel-cycle analysis. In both cases there is still much uncertainty and some controversy on the fundamental nature of the analyses and on the data inputs required. Thus we present these examples not as definitive, but as illustrative of the type of information they can provide.

How much is clean air worth? Because it generally becomes increasingly expensive to reduce pollution as emission controls tighten, a fundamental question is how much money each bit of emissions control is worth. If the value of averting damage were known, then the degree of control could be set such that the total cost (control cost plus residual damage cost) is minimised. Normally, the cost of control is fairly well known, being a function of various control techniques. Similarly, damage is fairly easy to value for simple property destruction, such as corrosion of buildings and reduction of crop yields. But valuing damage to critical ecosystems or human health is not straightforward. As a result there are no universally accepted methods.

Several approaches are used to value human health, including:

- Human capital—the value of lost wages and associated medical costs from illness or injury and premature death.
- Value of statistical life—the imputed value from extrapolating human risk-averting behaviour. For example, if the market shows that inducing a worker to accept a job with an additional death risk of 1/1,000 a year requires extra wages of X dollars a year, then X multiplied by 1,000 would equal the value of a lost life.
- Willingness to pay—in which people are asked how much they would be willing to pay to avoid certain risks. These amounts are then extrapolated to find the equivalent value of a life.

In recent years the willingness to pay approach has become more widely used, because it holds more theoretical appeal for economists than other approaches. But beyond the obvious difficulty of finding accurate data, there are three important problems with this approach. First, measured willingness to pay can be quite different for the same issue depending on how the question is phrased, raising doubt about the measure's intrinsic utility. Second, willingness to pay to avoid a certain risk depends on the respondent's knowledge about the risk, which varies dramatically by geography, demography, education, and time, and which are quite difficult to account for in surveys. Finally, although it is clear that willingness to pay varies with income, it is not clear by how much. As people grow richer, their willingness to pay to avoid a given risk generally increases even faster. But this relationship is not clear across different periods and cultures.

Consider some examples of how willingness to pay has been used to value air pollution in developing and industrialised countries. In China coal, the dirtiest fossil fuel, is widely used, its use is expected to grow rapidly in the next few decades, and effective pollution controls are not widely used. A recent study estimated that air pollution cost China about $48 billion in 1995 (7 percent of GDP), including impacts of acid deposition as well as health effects from outdoor and indoor air pollution (World Bank, 1997). The study found that the dominant cost came from health costs for urban residents, some $32 billion (5 percent of GDP). Moreover, it projected that

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under business as usual conditions, pollution-related health costs for urban residents would increase to $98 billion by 2020 at current income levels, or $390 billion (13 percent of GDP) with adjustments to willingness to pay related to growth in income. This is substantially more than the estimated economic damage of greenhouse gas emissions from the same facilities.

China's high pollution-related health costs are partly due to relatively limited pollution controls. Even in countries with relatively extensive pollution controls, however, pollution-related health costs can be high because aggregate energy-related emissions can be high even if emissions per unit of energy provided are low. Moreover, the willingness to pay to avoid pollution damages will be high in high-income countries. And in densely populated regions such as Europe and Japan, large populations are generally exposed to air pollution.

Recent studies in Europe have shown that health impacts dominate the external social costs of pollution, and estimate that the costs of health impacts due to fine particle air pollution are especially high (Rabl and Spadaro, 2000; Spadaro and Rabl, 1998; Spadaro and others, 1998; Krewitt and others, 1999). These economic calculations reflect recent epidemiological studies indicating that fine particles are associated with serious health effects, including premature death (see the section on the community scale).

Although considerable uncertainty remains about health impacts from small particles, the economic value of these impacts is expected to be high—at least in densely populated regions of high-income countries, where large populations are exposed to air pollution that can shorten lives by a few months. These populations are willing to pay considerable amounts to avoid this life shortening. Table 3.8 presents recent estimates of the health impacts of coal and natural gas power plants equipped with the best available control technologies. For natural gas combined-cycle plants the only significant health costs are associated with nitrogen oxide emissions, and these costs are relatively low (typically about 5 percent of the electricity generation cost). But for coal the estimated health costs (mostly due to chronic mortality from fine particle air pollutants) are large and comparable to the electricity generation cost. These estimates are quite uncertain, however.

Table 3.9 presents estimates of health costs in France for air pollution from gasoline-fuelled cars equipped with pollution controls and for diesel-fuelled cars. The estimated health impacts, measured per litre of fuel sold, are high (though, as with power generation, quite uncertain), especially for urban driving—about twice the retail price (excluding retail taxes) for gasoline cars and 25 times the retail price for diesel cars. As in China, the economic costs of greenhouse gas emissions from European cars and power plants would seem to be much lower.

These costs will vary significantly by region depending on the mix of rural and urban driving, whether emissions are at ground level or from tall stacks, local and regional population densities, and income, which affects willingness to pay. Applying the results in table 3.9 to developing countries, where per capita income averaged about $2,800 in 1995, the imputed health costs would be 0.1–0.5 times those estimated for France when all other factors are equal, depending on how willingness to pay varies with income.

If willingness to pay continues to increase more rapidly than income, health impacts will become increasingly important for developing countries even if emission controls are put in place. That is because their income and energy consumption levels will rise, increasing more rapidly than energy consumption levels, even with emission controls in place. To illustrate, consider the WEC projection that in developing countries the number of cars will increase 6-fold between 1990 and 2020 (WEC, 1995). Even if all were gasoline-fuelled cars equipped with three-way catalytic converters, health costs in developing countries would increase to $40–120 billion in 2020, depending on the rate of increase in willingness to pay. If all cars were diesel, health costs would be six times as high. These

TABLE 3.8. AIR POLLUTANT EMISSIONS AND ESTIMATED HEALTH COSTS FOR EUROPEAN POWER PLANTS EQUIPPED WITH THE BEST AVAILABLE CONTROL TECHNOLOGIES

Siting	Unit health cost (cents per gram)			Emission rate (grams per kilowatt-hour)				Unit health cost (cents per kilowatt-hour)				
				Pulverised coal steam-electric			Natural gas combined cycle	Pulverised coal steam-electric				Natural gas combined cycle
	Sulphur dioxide	Nitrogen oxides	PM_{10}	Sulphur dioxide	Nitrogen oxides	PM_{10}	Nitrogen oxides	Sulphur dioxide	Nitrogen oxides	PM_{10}	Total	Nitrogen oxides
Typical	1.0	1.6	1.7	1.0	2.0	0.2	0.1[a]	1.0	3.2	0.3	4.5	0.16
Urban	1.6	2.3	5.1	1.0	2.0	0.2	0.1[a]	1.6	4.6	0.5	6.7	0.23
Rural	0.7	1.1	0.5	1.0	2.0	0.2	0.1[a]	0.7	2.2	0.1	3.0	0.11

Note: These calculations were carried out as part of the European Commission's ExternE Program. Studies under the program have estimated the economic values of health impacts by assessing people's willingness to pay to avoid adverse health effects. The health cost estimates shown are median values; the 68 percent confidence interval is 0.25–4.0 times the median cost.

Source: Rabl and Spadaro, 2000.

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TABLE 3.9. AUTOMOTIVE NITROGEN OXIDE AND PARTICULATE EMISSIONS AND ASSOCIATED PUBLIC HEALTH COSTS IN FRANCE

Fuel and driving environment	Fuel economy (kilometres per litre)	Emission rate (grams per kilometre)		Health costs (dollars)							
				Per gram		Per kilometre			Per litre of fuel		
		Nitrogen oxides	Particulates	Nitrogen oxides	Particulates	Nitrogen oxides	Particulates	Total	Nitrogen oxides	Particulates	Total
Gasoline											
Urban	8.7	0.68	0.017	0.022	2.750	0.015	0.047	0.062	0.13	0.41	0.54
Rural	10.3	0.79	0.015	0.027	0.188	0.021	0.003	0.024	0.22	0.03	0.25
Diesel											
Urban	10.4	0.75	0.174	0.022	2.750	0.017	0.479	0.496	0.17	4.98	5.15
Rural	12.7	0.62	0.150	0.027	0.188	0.017	0.028	0.045	0.21	0.36	0.57

Note: These calculations were carried out as part of the European Commission's ExternE Program. Studies under the program have estimated the economic values of health impacts by assessing people's willingness to pay to avoid adverse health effects. The health cost estimates shown are median values; the 68 percent confidence interval is 0.25–4.0 times the median cost. The gasoline cases are for cars equipped with catalytic converters.

Source: Spadaro and Rabl, 1998; Spadaro and others, 1998.

health cost estimates do not include health impacts associated with buses, trucks, and locomotives, which are used much more widely than cars in developing countries and which are typically powered by diesel engines.

Health costs might end up being much higher than these estimates because real world emission levels tend to be considerably higher than regulated emission levels (Ross and others, 1995). That happens for a variety of reasons, including that regulated emissions are for well-maintained cars and that regulations tend to be for driving cycles that often do not reflect the way people actually drive.

These high estimated future health costs argue for much tighter emission controls than can be achieved with widely used current technologies. How much additional control will be needed? This is one of the critical questions for providing sustainable transport systems for the world's cities. Nevertheless, despite large uncertainties due to the willingness to pay method as well as to basic understanding of air pollution health effects, it seems safe to conclude that the economic value of air pollution abatement is substantial in developing and industrialised countries alike.

Fuel cycle analysis. Supplying modern energy often involves processes at a chain of facilities that may be quite physically distinct from one another. These processes are usually referred to as 'fuel cycles', although they rarely rely on any cycling. Comparisons based on fuel cycles are useful for organising impact analyses of energy supply and demand.

Consider the fuel cycle supporting the operation of an electric appliance. It may involve a coal mine, coal washery, coal train, coal power plant, and transmission lines, as well as ancillary facilities such as coal tailings piles, washery settling lagoons, and power-plant ash disposal. Each of these facilities has environmental impacts and is, in a sense, 'switched on' whenever the appliance is used even though it may be physically unconnected and thousands of kilometres away. Furthermore, environmental impacts occur not only during normal operations of these facilities, but also during their construction, repair, and dismantling—what is called their life cycle. Even non-fuel energy systems, such as photovoltaic power plants, have fuel cycles and life cycles, including the harvesting, processing, and transport of the materials used to construct the facility.

Comparative risk assessment is one term used for studies of the life-cycle impacts of alternative fuel cycles, such as different ways to produce electric power. Such studies are usually normalised according to an appropriate unit of energy output—for example, impacts may be scaled per kilowatt-hour or per barrel of oil equivalent. The idea is that in this way all the impacts can be fairly compared across alternative energy systems, giving full and consistent information to decision-makers. Such studies first account for insults over the life cycle of each part of the fuel cycle, such as land used, tonnes of pollution released, long-term waste generated, water consumed, and labour required per unit of output. Then most comparative risk assessments try to convert as many insults as possible into impacts with common measures, such as deaths, injuries, illnesses, and financial damage costs. Since the occupational impacts of energy systems can be significant (see the section on the workplace scale), often both public and worker risks are determined (box 3.10).

In addition to the methodological and other problems of fuel-cycle analysis and comparative risk assessment mentioned in box 3.10, there are some fundamental concerns with these kinds of comparisons that revolve around the unit of analysis—that is, the production of a certain amount of energy. For occupational impacts, for example, the number of accidents or illnesses per unit of energy output is just as much a measure of labour intensity as of safety. Indeed, from a societal standpoint, putting many people to work in low-risk activities is much better than employing a few people in high-risk activities. But both look the same in the comparisons.

In addition, by using energy as the output measure, such analyses reveal little about the impact of such facilities on overall public health, which uses time as the risk denominator. It may be that one

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way of producing electricity has slightly different public health implications than another, but neither may have much significance overall or, conversely, neither may be acceptable. Entirely different kinds of analyses are needed to evaluate these kinds of questions.

It is difficult to envisage a sustainable energy future in which unprocessed solid fuels remain an important source of energy for a significant fraction of the world's households.

Implications for the future

As noted in the introduction, there has not been space in this chapter to present what is known and suspected about the many environmental insults of different energy systems and the resulting impacts on ecosystems and human health. But we have addressed a large fraction of the most important ones. The central task of this report is to outline the main characteristics of a sustainable energy future. Thus it is appropriate to examine the main categories of insults and impacts discussed in this chapter to see what requirements they impose on such a future.

Household scale

About half of the world's households use solid fuels (biomass and coal) for cooking and heating in simple devices that produce large amounts of air pollution. Because the pollution is released at the times and places where people spend time, the health impact is high, accounting for 4–5 percent of the global burden of disease. The chief ecosystem impact relates to charcoal production and urban fuelwood harvesting, which puts pressure on forests near cities and may account for a few percentage points of global deforestation.

It is difficult to envisage a sustainable energy future in which unprocessed solid fuels remain an important source of energy for a significant fraction of the world's households. Gases, liquids, and electricity are the main clean alternatives. Although today these alternatives mostly derive from fossil fuels, this need not be the case in the future. In the future these alternatives may be made from renewable biomass fuels such as wood and crop residues (see chapters 7, 8, and 10). Indeed, a further criterion for sustainable energy is that any biomass harvested to make household fuels should be done on a renewable basis to ease pressure on forests and other natural ecosystems.

Workplace scale

The harvesting of solid fuels (biomass, coal, uranium) creates the highest risks per energy worker and the largest impacts on the energy workforce world-wide. Risks to coal miners, for example, are many times those for the average industrial worker. To be sustainable, average miner risks will probably have to be lowered to those in the safest mines today.

Community scale

Fuel use is the chief cause of urban air pollution, though there is substantial variation among cities in the relative contributions of vehicles and stationary sources. Diesel-fuelled vehicles, which are more prominent in developing countries, pose a growing challenge to meeting urban health-related pollution guidelines (responsible for about 1 percent of the global burden of disease).

To be sustainable, mean urban air pollution around the world will need to be no greater than what is common in rich countries today—for example, less than 30 micrograms per cubic metre of PM10. An additional requirement for sustainability is that urban ambient ozone levels not rise as vehicle fleets grow. Sufficiently clean power generation by fossil and nuclear sources is technically feasible, although costs are uncertain (see chapter 8). Similarly, hybrid vehicles are substantially cleaner than current types (see box 3.5). Achieving sustainability, however, will probably require moving most of the world's fleet to fuel cells or comparably clean systems by the middle of the 21st century.

Regional scale

The problem of regional atmospheric emissions will not go away quickly. The increasing demand for energy, especially in developing countries, will put heavy pressure on cheap and easily obtainable fossil fuels such as coal and oil. Prospects for constraining increases in regional emissions are better for some pollutants and source types. An ambitious goal for sulphur dioxide emissions, for example, would be a 50 percent reduction world-wide by 2050. This goal could be achieved by reducing the sulphur content of fossil fuels and using emission controls on new, large power plants and industrial facilities. Switching to natural gas in developing countries would also considerably aid the achievement of this goal. Increases in sulphur dioxide emissions in the developing world will be offset by legislatively driven reductions in industrialised countries.

Nitrogen oxide emissions are a bigger problem. The expansion of transportation systems in developing countries will add to the nitrogen oxide burden from industrial production and power generation. Moreover, nitrogen oxides are much harder to control than sulphur dioxide. An ambitious goal would be to stabilise nitrogen oxide emissions at current levels by 2050. Only a major shift away from fossil fuels in all parts of the world or a shift to alternate energy carriers such as hydrogen derived from fossil fuels will enable this goal to be achieved.

Carbon monoxide emissions will likely fall significantly as developing countries move away from biofuels and as automobiles become more efficient world-wide. Emissions of volatile organic compounds from energy sources will likely be reduced, but large increases can be expected from non-energy sources, particularly as the commercial and residential use of solvents increases in the developing world. Holding global emissions of volatile organic compounds to a 20–50 percent increase by 2050 will be a challenge. The faster that clean and efficient vehicles and fuels can replace current vehicles and fuels, the greater will be the reduction in emissions of nitrogen oxides, carbon monoxide, and volatile organic compounds.

It seems that acid deposition world-wide will increasingly become a nitrogen oxide (and possibly an ammonia) problem rather than a

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BOX 3.10. COMPARATIVE RISK ASSESSMENT USING FUEL-CYCLE ANALYSIS

A number of concerns drive the need to assess the environmental and human health damage associated with electricity production. These include informing utility planning decisions in terms of total social costs, enlightening cost-benefit analyses of pollution mitigation technologies, facilitating formulation of regulatory procedures, and delineating the secondary benefits of reducing greenhouse gas emissions. Attempts to quantify damages incurred by electricity generation technologies date to the 1970s and are known as fuel-cycle analyses or comparative risk assessments. Most fuel-cycle analyses have been undertaken in industrialised countries, but a few have considered electricity production in developing countries (such as Lazarus and others, 1995).

Fuel-cycle analyses attempt to account for all damages caused by physical and chemical processes and activities undertaken to generate electricity from a specific fuel or resource, from fuel acquisition to waste disposal in a steady-state operations approach, or from construction to decommissioning in a facility lifetime approach. Because different insults exert their impacts over different temporal and spatial scales, the geographic extent and time horizon of an analysis must be carefully defined to cover all significant impacts. Contemporary fuel-cycle analyses generally follow a damage function or impact pathway approach whereby dominant impacts are identified; stresses (incremental population exposures to air pollution, occupational hazards, transportation risks) are quantified; stresses are translated to impacts, typically through exposure-response functions or actuarial data; and impacts are quantified and aggregated in terms of the study's chosen metric (ORNL and RFF, 1992; Curtiss and Rabl, 1996). The study design stage entails a number of choices on impacts to be considered (public and occupational health, ecological damage, agricultural losses, material corrosion, visual amenity), temporal and spatial assessment boundaries, models and hypotheses for analysis, economic parameters such as the discount rate, and the treatment of accident scenarios for which no actuarial data exist (such as expected and worst case).

A fuel-cycle analysis typically results in a list of impacts per unit of output in the form of premature deaths, ecosystem damage, global warming, and the like. To provide a common metric for comparison, many studies then attempt to monetise these impacts. This process introduces substantially more uncertainty and controversy into the process.

Fuel-cycle analyses have typically generated 'total cost' figures in terms of m$ ($0.001) or mECU per kilowatt-hour, with recent (post-1990) European and U.S. estimates ranging from 0.016–80 m$ per kilowatt-hour for coal and from 0.002–23 m$ per kilowatt-hour for nuclear (Rabl and Spadaro, 2000). Given the four orders of magnitude spanned by these fuel chain damage costs, it is clear that they are sensitive to the particular designs and metrics of the studies. Accordingly, interpretation of studies' results requires extensive supplementary information to illuminate, for example, the specific impacts assessed and the study-specific approaches to valuation of life, valuation of non-fatal outcomes, weighting of public and occupational health outcomes, and discount rates. Thus fuel-cycle analysis damage costs cannot stand alone and are difficult to compare, despite the fact that they may superficially appear to be based on comparable metrics (dollars per kilowatt-hour).

Although comparative risk assessment using fuel-cycle analysis cannot yet indicate unambiguous preferences or even readily allow for comparisons between studies, recent studies suggest that public health and occupational health effects dominate the externalities associated with the nuclear fuel chain. Health effects and global warming dominate conventional coal technologies (Rabl and Spadaro, 2000). Biomass as an energy resource is less easily characterised even in terms of dominant impacts because it is highly dispersed, the nature of its production and use is extremely site-specific, and its associated damages and benefits depend on other local activities such as agriculture (Lazarus and others, 1995). Similarly, hydroelectric utilities elude concise generalisation due to the wide range of sophistication among technologies and the site-specificity of ecological and human health risks. Fuel-cycle analyses yield widely disparate conclusions for solar thermal and dispersed photovoltaic technologies. Some studies, particularly those focusing on operation of energy systems, suggest that these solar technologies confer negligible human health and ecological risks (Rabl and Spadaro, 2000). Other studies assert that the occupational risks and short-term environmental damage associated with solar technologies can exceed those of conventional electricity generation methods (Hallenbeck, 1995, Bezdek 1993).

Pitfalls associated with fuel-cycle analysis include the use of poorly defined or inconsistent study boundaries, confusion of average and marginal effects, underestimation of the uncertainty associated with quantification of damages, neglect or inadequate treatment of environmental stochasticity, and focus on what is easily quantified rather than on what is actually significant (Koomey, 1990).

A number of outstanding issues remain for streamlining approaches to fuel-cycle analysis. These issues include identifying the functional relations and key parameters defining uncertainty, the variation in damages with key parameters, the degree of accuracy and resolution with regard to atmospheric modelling and receptor distribution (needed to capture the site-specificity of impacts), and the magnitude of error incurred by using 'typical' average values rather than detailed, site-specific data (Curtiss and Rabl, 1996). In addition, metrics used in fuel-cycle analysis to deal with incommensurate impacts—such as the soiling of buildings, crop damage, and human morbidity and mortality—are not uniform between studies.

sulphur dioxide problem. On balance, reductions in acidification in Europe and North America are likely to continue, but hotspots of damage in the developing world (such as southwestern China) may persist for years and worsen. Regional ozone will increasingly be the biggest problem because of the expected difficulties in mitigating emissions of nitrogen oxides and volatile organic compounds, the two main precursors of ozone. Only small improvements in regional ozone levels may occur in North America and Europe in the next 10–20 years. And considerable deterioration is likely in Asia, Africa, and Latin America, endangering human health and agricultural production.

Large dams will continue to provide potential for significant benefits and severe environmental impacts, depending on their location and design. For sustainability, much better evaluation will be needed to maximise the benefits and minimise the environmental impacts.

Global scale

Energy systems generate two-thirds of human-caused greenhouse gases. Thus energy use is the human activity most closely linked to the potential for climate change. Climate change is feared to entail significant direct impacts on human health as well as on Earth's ecosystems. As noted, there has been a tendency for environmental problems at the local level to be solved partly by pushing off the impacts to larger scales. Greenhouse gases and their potential for global climate change represent the final and, in many ways, most challenging of the stages. Although there are promising technologies for fossil systems that capture and sequester the greenhouse gases resulting from combustion, as well as fossil, nuclear, and solar systems releasing no greenhouse gases, their prospects are not entirely understood (see chapters 7 and 8).

It is difficult to define a sustainable level of greenhouse warming

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A sampling of results from fuel-cycle analyses, which have been used in a variety of contexts, follows:

- An investigation of externalities of electricity production from biomass and coal in the Netherlands suggests that while average private costs for the biomass strategy assessed are projected to be about twice those for coal in 2005, internalisation of external damages and benefits would yield about equal social costs. The most important distinguishing factors between coal and biomass are differences in carbon dioxide emissions and indirect economic effects such as employment (Faaij and others, 1998).
- A comparison of fuel-intensive combustion-based utilities (coal, oil, gas, and biomass), selected renewable energy technologies (solar thermal, photovoltaic, wind, and hydroelectric), and nuclear technologies (light water reactor, fast breeder reactor, and hypothetical fusion reactor) suggests that coal inflicts the greatest delayed occupational health burden (such as disease), with a central estimate of 0.1 fatalities per GWy(e) and an upper estimate of about 3 fatalities per GWy(e). Acute occupational risks (such as accidents) posed by combustion technologies are purported to be marginally less than those associated with renewable energy technologies—with central estimates on the order of 1 fatality per GWy(e)—but greater by an order of magnitude than those associated with fission technologies and comparable to those for fusion. In the public health domain, with central estimates of about 2 fatalities per GWy(e), coal and oil appear to confer greater delayed mortality burdens by a factor of two (relative to photovoltaic systems) to three or four orders of magnitude (relative to wind, hydroelectric, and nuclear technologies). While acute risks associated with renewable energy technologies are highly uncertain, this study places them as comparable to or somewhat higher than those associated with fuel-intensive combustion technologies, at 0.1–1.0 fatalities per GWy(e) (Fritzsche, 1989).
- A study by the Stockholm Environmental Institute suggests that in terms of greenhouse gas emissions, natural gas is preferred to residual fuel for electricity generation in Venezuela, even under the assumption of relatively high methane emissions through natural gas system losses. In this context the global warming potential per kilowatt-hour of natural gas electricity generation is projected to be 12–27 percent lower than that associated with residual fuel (Lazarus and others, 1995).
- Since the early 1990s several studies have tried to quantify greenhouse gas emissions associated with different fuel cycles (see table below). Some of the variability arises from the different conversion efficiencies of the technologies assessed—for example, biomass configurations include a wood steam boiler, an atmospheric fluidised bed combustor, and an integrated gasifier combined-cycle turbine. But methodological issues and assumptions associated with activities outside the generation stage account for a large portion of the variability. For example, one study credits product heat from cogeneration cycles for displacing greenhouse gases from gas heating systems (Fritsche, 1992). In this framework the greenhouse gas intensity of biomass can become negative, and that of natural gas fuel cycles can be reduced 50 percent below the next lowest estimate. Among fossil fuels, the greenhouse gas intensity of natural gas is most variable, primarily due to different assumptions about methane emissions during drilling, processing, and transport. For non-fossil fuels, estimates generally span at least an order of magnitude, primarily because of the sensitivity of these cycles to assumptions on the operation life of the facility and the greenhouse gas intensity of the electric and manufacturing sectors on which equipment production depends. In addition, the hydroelectric cycle's greenhouse gas intensity is sensitive to the area of land flooded and, for projects with multiple generating units per reservoir, the boundary of the system considered.

Box table. Greenhouse gas emission intensities for selected fuels (grams of carbon dioxide equivalent per kilowatt-hour)

Conventional coal	Advanced coal	Oil	Gas	Nuclear	Biomass	Photovoltaic	Hydroelectric	Wind
960-1,300	800-860	690-870	460-1,230[a]	9-100	37-166[a]	30-150	2-410	11-75

Note: These estimates encompass a range of technologies and countries as described in Pearce and Bann, 1992; Fritsche, 1992; Yasukawa and others, 1992; ORNL and RFF 1992–98; Gagnon and van de Vate, 1997; and Rogner and Khan, 1998.

a. Natural gas and biomass fuel cycles were also analysed in cogeneration configurations, with product heat credited for displacing greenhouse gas emissions from gas heating systems. That approach reduced greenhouse gas emissions to 220 grams of carbon dioxide equivalent per kilowatt-hour for natural gas and –400 for biomass (Fritsche 1992). Other cycles could incorporate cogeneration and be analysed in this manner.

above the natural background. Achieving something akin to the natural background, on the other hand, will not be possible for many centuries, barring major, unprecedented, and unforeseen technical breakthroughs, global catastrophes, or changes in human behaviour. What then, might be considered a workable definition of 'sustainable' for the climate change impacts of the world energy system?

The coming climate change can be considered in two parts: magnitude (total warming) and rate (annual increase). Some types of impacts are more sensitive to one than the other. For example, sea level rise is more sensitive to magnitude, and ecosystem damage is more sensitive to rate. Perhaps the most worrisome aspect of human-engendered warming, however, is that it threatens to cause warming at rates completely unprecedented in Earth's recent geologic history. The magnitude of potential change is somewhat less unprecedented. Thus it may be reasonable to establish a somewhat less stringent definition of sustainability for greenhouse gas emissions—one that calls for stabilising atmospheric levels as quickly as possible, recognising that the resulting levels (and their warming) will be considerably higher than the natural background.

Achieving stable atmospheric levels during the 21st century will require bringing human greenhouse gas emissions to annual rates substantially below those today. Doing so will not be easy. Indeed, it will require major commitments of resources and political will (see the section on the global scale and chapter 9). The longer such efforts are delayed, the higher and longer will be the eventual stable warming level and accompanying impacts.

Reaching emission levels in 2050 below those in 2000 will probably require annual declines in energy intensity of at least 1.4 percent and in carbon intensity of energy of at least 0.4 percent . With the assumptions in table 9.1, even these major accomplishments

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would still allow emissions growth of 0.4 percent a year to 22 percent above 2000 emissions by 2050. With such modest growth, however, and 50 years of experience promoting efficient and low-carbon energy sources, it might be possible to achieve emissions below 2000 levels within a few years after 2050.

Cross-scale

There are important opportunities for 'no regrets' strategies that achieve benefits at more than one scale. For example, if greenhouse gas controls are targeted towards reducing solid fuel use in households and in other energy systems with large health impacts (such as vehicle fleets), significant improvements can occur at the local, community, and global scales. Fine particles are generated and have impacts at all scales, so control measures will benefit from integrated approaches. Similarly, the regional impacts from sulphur and nitrogen emissions can be reduced in conjunction with control efforts at the community and global scales. Much additional effort is needed to identify environmental control pathways that optimise these multiple benefits.

Conclusion

Impacts other than those discussed in this chapter need to be considered, particularly in local situations. But if the environmental insults and their ecosystem and health impacts focused on here were controlled as indicated, the world would have moved most of the way towards a sustainable energy system.

Among the other impacts requiring careful consideration are the relationships between energy systems and military, political, and economic security—the subjects of the next chapter. ■

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Notes

1. *Insult* is defined here as the physical stressor (such as air pollution) produced by an energy system. Impact, in contrast, is defined as the potential negative (or positive) outcome (such as respiratory disease or forest destruction) affecting humanity. As with other useful terms (diagnosis, prognosis, pathology) the term insult is borrowed from medicine, where it is defined as "a generic term for any stressful stimulus, which under normal circumstances does not affect the host organism, but may result in morbidity when it occurs in a background of pre-existing compromising conditions" (Segen, 1992). It has been used in environmental discussions, however, since at least the mid-1970s (see Ehrlich and others, 1977).

2. Modern fuels involve extensive fuel cycles with relevant environmental impacts and energy efficiencies at several points. The air pollution exposures per meal are still lower than that from solid fuels, however.

3. The burden of disease refers to the total healthy life years lost due to this risk factor. It is composed of two parts that are added together: life years lost to deaths and life years lost to diseases and injuries weighted by a severity factor.

4. These include the main gaseous pollutants as well as particulates. For lead emissions, the overall reduction in hazard per vehicle mile was about 75 percent (US Census Bureau, 1996; USEPA, 1996).

5. PM_{10} are particles less than 10 microns (millionths of a meter) in size, which penetrate deeper into the respiratory system than larger particles.

6. The World Commission on Dams, which began deliberating in 1998, is publishing its reports in mid-2000 (WCD, 1999). These will include 8–10 case studies examining social, economic, environmental, energy, financial, managerial, and other aspects plus a database of 150 dams in different countries.

7. This section draws heavily on IPCC (1996a, b). The IPCC was established by the World Meteorological Organization and United Nations Environment Programme in 1988 to assess the scientific, technological, economic, and social aspects of anthropogenic climate change. Some 2,000 scientists and other specialists from more than 40 countries served as authors and reviewers of the 17 volumes of exposition and analysis issued by the IPCC through 1996. The IPCC's first assessment report, completed in late 1990, served as the basis for the negotiations of the United Nations Framework Convention on Climate Change, concluded in 1992 and discussed below.

8. The mean global surface temperature of the Earth is about 15 degrees Celsius (59 degrees Fahrenheit). Without greenhouse gases, it would be –18 degrees Celsius (0 degrees Fahrenheit).

9. Combustion emits water vapour and carbon dioxide in comparable quantities. But the rate of water addition to the global atmosphere by combustion is tens of thousands of times smaller than the rates of addition and removal by evaporation and precipitation. And because the added water remains in the atmosphere only a few days, these human additions cause at most local effects and no long-term build-up. In contrast, the quantity of carbon dioxide added by combustion is only about 10 times smaller than what is added and removed by natural photosynthesis and decomposition, and a large part of the anthropogenic increment remains in the atmosphere for decades. Thus it has time to become uniformly distributed around the globe, irrespective of where it was emitted, and to accumulate over long periods (as long as the sum of the natural and anthropogenic addition rates is greater than the removal rate).

10. There is no net accumulation of carbon dioxide in the atmosphere from combustion of wood and other biomass fuels, however, as long as new plant growth replaces what is burned. This is because a growing plant removes from the atmosphere exactly as much carbon dioxide as is released when the plant decomposes or burns. When new growth does not replace what is burned or decomposed, however, as in deforestation, a net addition of carbon dioxide to the atmosphere results. (See the section on greenhouse gas emissions at the household scale, however, for a discussion of non–carbon dioxide greenhouse gas emissions from incomplete biomass combustion.)

11. Feedbacks are phenomena wherein the consequences of a disturbance act back on its cause, making the disturbance either bigger (positive feedback) or smaller (negative feedback) than it started out.

12. The first and longest-running series of measurements was initiated by Charles Keeling at a monitoring station atop the Mauna Loa volcano on the island of Hawaii.

13. The main such terrestrial 'sinks' for atmospheric carbon are in the Northern hemisphere (see Houghton, 1996 and Fan and others, 1998).

14. Particles in the atmosphere exert both cooling and warming effects on the Earth's surface temperature, depending on the characteristics of the specific particles in terms of absorption and scattering of incoming solar and outgoing terrestrial radiation, and on the roles of different particles in cloud formation. Averaged over the globe and the different types of anthropogenic particles, the net effect is cooling.

15. Because particulate matter and its gaseous precursors have much shorter residence times in the atmosphere than any of the major greenhouse gases, its offset of part of the greenhouse effect will shrink in line with declining particulate and precursor emissions.

16. This range corresponds to 0.54–1.08 degrees Fahrenheit, but the two-significant-figure precision resulting from applying the exact conversion (1 degree Celsius = 1.8 degrees Fahrenheit) is illusory. The warming is not uniform, however, being generally greater near the poles than near the equator. And because of the complexity of the heat transfer processes of the climatic system, some regions may get colder even as the globe gets warmer on average.

17. The most sophisticated models demonstrate the fundamental soundness of their representations of global climatic processes by simulating quite accurately the undisturbed climate of the planet in respects such as the variation of geographic patterns of temperature and precipitation with the changes of the seasons.

18. Temperatures would continue to rise thereafter, even in the cases in which the atmospheric concentrations of greenhouse gases had been stabilised by then, because of the climate-response lag time caused by the thermal inertia of the oceans.

19. Non-linear means that small disturbances can have large consequences. Forcing is the technical term for an externally imposed disturbance, such as a change in greenhouse gas concentrations. An example of a potential positive feedback on global warming from terrestrial ecosystems is that the warming could increase the rate of release of greenhouse gases into the atmosphere from decomposition of dead organic matter in forests and swamps.

20. The discussion here is drawn from a treatment prepared by one of the authors (Holdren) for the report of the Panel on International Cooperation in Energy Research, Development, Demonstration, and Deployment, President's Committee of Advisors on Science and Technology (PCAST, 1999).

21. See IPCC (1996b). Both trends—an increase in rainfall and an increase in the fraction of it occurring in extreme events—have been convincingly documented for the period since 1900 in the United States (Karl and Knight, 1998).

22. The improvements in agricultural productivity foreseen for some regions by the IPCC are due partly to carbon dioxide fertilisation of plant growth, partly to increased water availability from increased precipitation, and partly to technological change. Although the IPCC discusses at length how plant pests and pathogens could prove increasingly problematic in a greenhouse gas–warmed world, these possibilities do not seem to be fully reflected in the productivity projections.

23. This section draws heavily on material written by one of the authors (Holdren) for the report of the Panel on Federal Energy Research and Development, President's Committee of Advisors on Science and Technology (PCAST, 1997).

24. Annex 1 countries, as defined in the UNFCCC, are OECD countries plus the countries of Eastern Europe and some of those of the former Soviet Union (the Baltics, Belarus, Russia, Ukraine).

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