Energy and Human Health

Kirk R. Smith,[1] Howard Frumkin,[3] Kalpana Balakrishnan,[4]
Colin D. Butler,[5] Zoë A. Chafe,[1,2] Ian Fairlie,[6] Patrick Kinney,[7]
Tord Kjellstrom,[8] Denise L. Mauzerall,[9] Thomas E. McKone,[1,10]
Anthony J. McMichael,[11] and Mycle Schneider[12]

[1] School of Public Health, [2] Energy and Resources Group, University of California, Berkeley, California 94720-7360; email: krksmith@berkeley.edu, zoe.chafe@berkeley.edu

[3] School of Public Health, University of Washington, Seattle, Washington 98195; email: frumkin@uw.edu

[4] Department of Environmental Health Engineering, Sri Ramachandra University, Porur, Chennai-600116, India; email: kalpanasrmc@ehe.org.in

[5] Discipline of Public Health, Faculty of Health, University of Canberra, Canberra, ACT 2601, Australia; email: colin.butler@canberra.edu.au

[6] Independent Consultant on Radioactivity in the Environment, United Kingdom; email: ianfairlie@gmail.com

[7] Department of Environmental Health Sciences, Mailman School of Public Health, Columbia University, New York, NY 10032; email: plk3@columbia.edu

[8] Center for Global Health Research, Umeå University, SE-90187 Umeå, Sweden; and National Center for Epidemiology and Population Health, Australian National University, Canberra ACT 0200 Australia; email: kjellstromt@yahoo.com

[9] Woodrow Wilson School of Public and International Affairs and Department of Civil and Environmental Engineering, Princeton University, Princeton, New Jersey 08544; email: mauzeral@princeton.edu

[10] Lawrence Berkeley National Laboratory, Berkeley, California 94720; email: temckone@lbl.gov

[11] National Centre for Epidemiology and Population Health, The Australian National University, Canberra, ACT 0200, Australia; email: tony.mcmichael@anu.edu.au

[12] Independent Consultant on Radioactivity in the Environment, France; email: mycle@wanadoo.fr

Annu. Rev. Public Health 2013. 34:159–88

The *Annual Review of Public Health* is online at publhealth.annualreviews.org

This article's doi:
10.1146/annurev-publhealth-031912-114404

Keywords

coal, air pollution, biomass fuel, petroleum, nuclear energy

Abstract

Energy use is central to human society and provides many health benefits. But each source of energy entails some health risks. This article reviews the health impacts of each major source of energy, focusing on those with major implications for the burden of disease globally. The biggest health impacts accrue to the harvesting and burning of solid fuels, coal and biomass, mainly in the form of occupational health risks and household and general ambient air pollution. Lack of access to clean fuels and electricity in the world's poor households is a particularly serious risk for health. Although energy efficiency brings many benefits, it also entails some health risks, as do renewable energy systems, if not managed carefully. We do not review health impacts of climate change itself, which are due mostly to climate-altering pollutants from energy systems, but do discuss the potential for achieving near-term health cobenefits by reducing certain climate-related emissions.

INTRODUCTION

Energy use is central to human activity for preparing food, warming homes, powering travel, and producing goods, among many other purposes. "The history of human culture," wrote one historian, "can be viewed as the progressive development of new energy sources and their associated conversion technologies" (76a, p. 318). Indeed, the control of wood fires for cooking arguably is the fundamental transformation that made humans distinct from other primates (232). Later, water and wind were tapped as energy sources. Burning animal products, such as whale oil, was important for a time. Modern history brought the use of coal and, later, natural gas, oil, and nuclear power. Contemporary societies mirror this history. Depending on the level of economic development, today's energy sources range from animal power and harvested or scavenged biomass (wood, dung, peat), to more processed biofuels (charcoal), to commercial fossil fuels and electricity (65).

Total energy use is related to population growth and economic output, but there is much variation in the effectiveness of energy use across societies (72). The amount of energy used, as well as the quality of energy, drives economic productivity; more efficient and flexible energy sources (liquid fuels and especially electricity) are associated with higher productivity (212). This notion is reflected in the concept of the fuel ladder (or energy ladder)—the idea that increasing development and wealth are marked by the use of progressively cleaner fuels processed farther from the point of use (89). Of course, energy availability is not the only driver of development; education and labor markets, women's rights, financial institutions, physical infrastructure, geography, and other factors also play central roles.

As with economic development, more energy use is associated with better health up to a point. Population metrics such as infant mortality and life expectancy improve until levels of ~2,000–3,000 kg of oil equivalent per person per year, then remain steady, although with much variation (65, 66). Energy availability is also associated with health at the household level, reflected in the terms "energy security" and "energy poverty". Energy security, at the household level, refers to a family's probability of having enough energy to cook food, heat the home during cold weather, and cool the home during warm weather—a matter of availability, affordability, and capacity (154). Energy poverty (or fuel poverty), conversely, refers to financial hardship in affording energy for these basic uses (16). Energy poverty is associated with many of the afflictions of economic poverty, including poor health and adverse social outcomes (34, 92).

Although they enhance and support health in many ways, all forms of energy use also have negative consequences. Since early times, technical advances in harnessing energy, from open fires (that burned people and property) to steam engines (that exploded), have made clear that intense exposure to energy can be dangerous. The Haddon injury matrix exemplifies this concept, using the energy of a moving automobile (derived from fossil fuel combustion) as the vector of injury (73).

But the adverse health impacts of energy are not limited to injuring people through direct mechanical and physical means. Throughout the energy life cycle, from initial fuel collection to energy production to disposal of waste products, adverse consequences may arise. In general, the pattern of energy risks follows that of the "environmental risk transition": Household risks predominate in poor societies, community-level risks predominate in middle-income societies, and higher-income societies contribute most to global risks (198). **Figure 1** shows pathways linking energy and health, distinguishing primary energy sources and the fuel cycles through which they are gathered and used to generate energy, from intermediate secondary energy forms such as electricity, and from end-use energy services such as transportation. Each stage has associated adverse health impacts. Energy is a health issue.

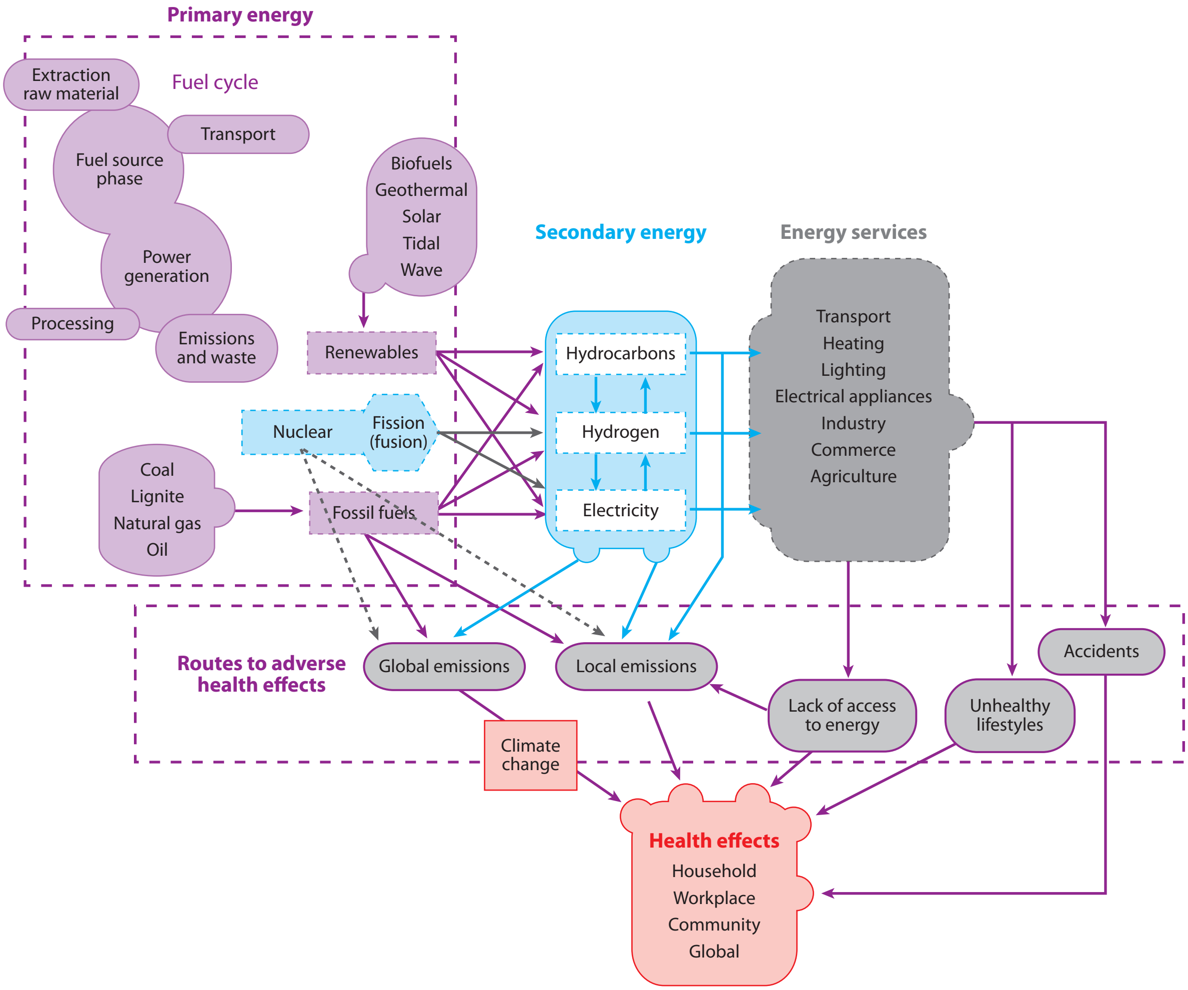

Figure 1

Pathways linking energy and health. From Reference 226.

For perspective, **Figure 2** depicts world energy consumption since the mid-nineteenth century. The largest energy sources used by humanity are the fossil fuels—petroleum, coal, and natural gas—so named because they were formed over millions of years from organic matter such as plants (and therefore represent stored solar energy). Biomass (wood, agricultural residues, peat, and animal dung) accounts for a smaller percent of all energy but serves the energy needs of much of the world's population. Electricity does not appear in **Figure 2** because it is a secondary energy source, formed mostly from combustion of fossil fuels, from nuclear reactions, and from falling water (in hydroelectric plants).

This review derives much information from the health chapter of the 2012 *Global Energy Assessment* (see acknowledgments) (196).[1] The focus of this article is on the short- and medium-term health risks associated with major energy production systems and energy

---

[1] It also draws on previous global work such as the *World Energy Assessment* (67) and the six-paper section "Energy and Health" in *Lancet* (74).

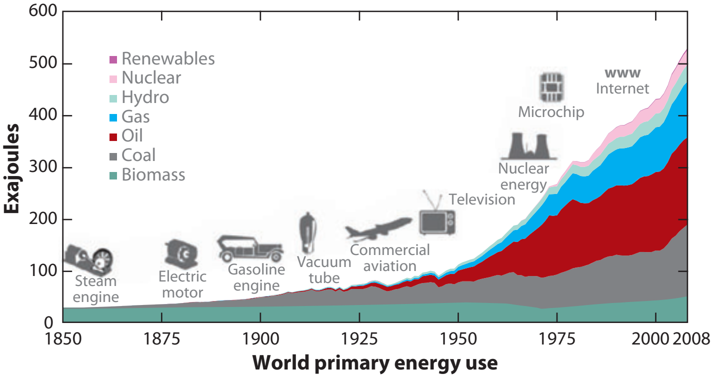

Figure 2

Evolution of primary energy sources, shown as absolute contributions by different energy sources. Biomass refers to traditional biomass until the most recent decades, when modern biomass became more prevalent and now accounts for one-quarter of biomass energy. New renewables appear in recent decades. Note that biomass energy has remained constant as other forms take larger roles. 1 exajoule ~ 1 million tons of oil equivalent. From Reference 65.

choices. We do not evaluate the long-term health risks associated with climate change that will be exacerbated by emissions of carbon dioxide (CO_2) and other climate-altering pollutants from energy systems.

HOUSEHOLD ENERGY

Patterns of Household Fuel Use

The *Global Energy Assessment* estimates that in 2005 ~2.8 billion people, mostly in the poorest countries, relied on solid fuels such as biomass, charcoal, and coal for cooking and other household energy needs (155). India and China together account for about half the global population that uses solid fuels for cooking (27% and 25%, respectively), closely followed by sub-Saharan Africa (21%) (215). The solid fuels used for household cooking vary across countries, e.g., charcoal in sub-Saharan Africa, coal in China, dung in India, and crop residues in Bangladesh (196). Within a country, both household poverty and rural location predict the use of solid fuels. Rising income, however, does not assure a smooth transition to cleaner fuels; availability, pricing policies, education, and cultural preferences play roles (133). Wood, humanity's oldest fuel, is still used wherever available, even in many high-income countries, as a heating fuel (203). Growing, collecting, and transporting wood, whether as paid employment or unpaid daily household activity, produce many of the same serious occupational health risks as the forestry industry (169).

HAP: household air pollution

$PM_{2.5}$: particles less than 2.5 μg in diameter

Exposure to Household Fuel Combustion Products

Poor households often burn fuel in inefficient, insufficiently vented combustion devices, resulting in considerable waste of fuel energy and emission of toxic products from incomplete combustion. The amounts and relative proportions of the various pollutants generated by solid fuel combustion depend on a number of factors, including fuel type and moisture content, stove technology, and operator behavior (106) (see **Table 1**). High levels of emissions in small, poorly ventilated rooms result in elevated household pollution concentrations and lead to significant exposures, particularly among women and children, who spend the most time in or near the kitchen. Very young children are especially at risk because they are highly exposed during vulnerable developmental periods.

Well over 200 measurement studies (9) over the past three decades have assessed levels of household air pollution (HAP) in developing countries. Whereas earlier studies focused on short-term, single-pollutant measurements to document the magnitude of exposures, several large-scale cross-sectional studies and some longitudinal studies now both provide individual- or population-level exposure information and characterize spatiotemporal (e.g., 11, 81) and interindividual variability (3, 11, 39, 135, 194, 201). Although we have no systematic worldwide measurements, available data show that levels of small particles ($PM_{2.5}$) are highest during cooking in homes burning dung (mean 7,800 ± 11,200 $\mu g/m^3$), followed by charcoal (mean 3,900 ± 8,400 $\mu g/m^3$) and wood (mean 2,100 ± 3,900 $\mu g/m^3$). PM levels in households using kerosene are roughly an order of magnitude lower, while those in households using exclusively gas or electricity are lower still (9).

Table 1 Pollutants from combustion of biomass and fossil fuels. Adapted from References 142 and 196

Pollutant	Known toxicologic characteristics
Particulates (PM_{10}, $PM_{2.5}$)	Bronchial irritation, inflammation, increased reactivity, reduced mucociliary clearance, reduced macrophage response, increased cardiovascular mortality
Carbon monoxide	Reduced oxygen delivery to tissues owing to formation of carboxyhemoglobin; can be acutely fatal
Nitrogen dioxide	Bronchial reactivity, increased susceptibility to bacterial and viral lung infections
Sulfur dioxide	Bronchial reactivity (other toxic end points common to particulate fractions)
Organic air pollutants:	
Formaldehyde	
1,3 butadiene	
Benzene	Carcinogenicity
Acetaldehyde	Co-carcinogenicity
Phenols	Mucus coagulation, cilia toxicity
Pyrene, Benzopyrene	Increased allergic sensitization
Benzo(a)pyrene	Increased airway reactivity
Dibenzopyrenes	
Dibenzocarbazoles	
Cresols	

Although particles and carbon monoxide are the most commonly measured pollutants, a range of other products of incomplete combustion is found in solid fuel smoke, including oxides of nitrogen, phenols, quinones/semiquinones, chlorinated acids such as methylene chloride, and dioxins. Additionally, combustion of coal may release sulfur oxides, heavy metals, arsenic, and fluorine. A typical solid fuel stove converts 6–20% of fuel into toxic substances. Animal studies indicate that at least 28 pollutants present in solid fuel smoke are toxic, including some 14 carcinogens and 4 cancer promoters (142). The International Agency for Research on Cancer classified emissions from household coal combustion as "carcinogenic to humans" (Group 1 carcinogen) and emissions from household combustion of biomass fuel (mainly wood) as "probably carcinogenic to humans" (Group 2A carcinogen), although it contains several individual Group 1 carcinogens (97).

Even spread over the day and year, the high PM levels found during cooking with solid fuels result in mean concentrations and exposures in excess of the pollutant-specific annual World Health Organization *Air Quality Guidelines* (231), often by 5–20 fold, and far above typical levels of secondhand tobacco smoke exposure (**Figure 3**). Exposures are influenced by multiple household-level and individual determinants, such as fuel type, kitchen location, use and maintenance of stoves, household layout and ventilation, time-activity profiles of household members, and behavioral practices (such as where children are located when family members are cooking) (196). Geographic location, weather, and local vegetation patterns also play roles.

Health Effects of Household Fuel Combustion

The 2010 Global Burden of Disease assessment includes a calculation of the health burden of HAP from solid fuel use for selected diseases with sufficient evidence: pneumonia in children younger than five, and chronic obstructive

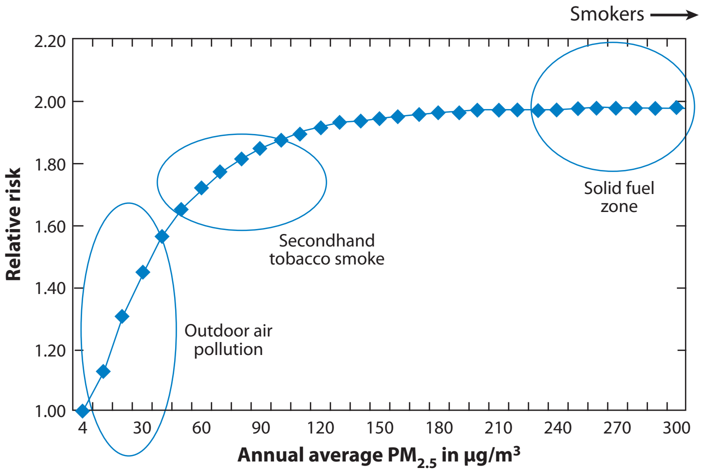

Figure 3

Relative exposure intensities of various forms of biomass fuel combustion, with associated risk of ischemic heart disease. $PM_{2.5}$, particles less than 2.5 µg in diameter. Based on References 126, 165, 211.

pulmonary disease (COPD), cardiovascular disease, cataracts, and lung cancer in adults. Although cardiovascular disease has not been tracked directly in these settings, other combustion particle studies (outdoor air pollution, environmental tobacco smoke, and active smoking) strongly suggest a major impact from combustion of household fuels as well (11, 165, 202, 211). Evidence of additional impacts from exposure to HAP is accumulating, including child cognitive function, low birth weight, and tuberculosis (40, 88, 168).

The 2010 Global Burden of Disease comparative risk assessment estimated that ~3.5 million premature deaths were caused by household cooking with solid fuels in 2010 (126). In terms of lost healthy life years (DALYs), HAP was the second most important risk factor among those examined for women worldwide, after high blood pressure, and was the fourth for men, after smoking, high blood pressure, and alcohol. In many poor regions, such as South Asia and much of sub-Saharan Africa, solid fuel use was the first or second most important risk factor for ill health among those examined, often rivaled by child malnutrition and far exceeding the burden of unsafe water and sanitation. In addition, household cooking with solid fuels accounted for an average of 16% of outdoor particle air pollution in the world, more in some regions than others. These data imply that the total impact of household solid fuels was ~4.8% of world DALYs and nearly 4 million premature deaths in 2010 (126).

Interventions to Protect Health

Household energy interventions have, to date, centered largely on reducing fuel use through more energy-efficient stoves (196). The ideal biomass stove would be energy-efficient and attain nearly complete combustion, thus reducing pollutant emissions, and of course must be well accepted by households to create benefits. It is not clear whether it is possible to achieve these goals with locally made stoves, however, because the need for heat-resistant materials such as alloys or ceramics, blowers, and good quality control seems to require centralized manufacture (12).

Although programs have achieved fuel-efficiency goals [e.g., the Chinese National Improved Stove Program placed stoves in some 180 million rural households during the 1980s and 1990s (192)], no large-scale cookstove program has yet achieved major smoke-reduction goals. Innovations are needed not only on the technical and behavioral sides, but also in financial and dissemination models. Technical advances center on cleaner-burning stoves, such as "gasifier" stoves, which achieve very high combustion efficiency through two-stage combustion designs, the cleanest including small electric blowers to stabilize the combustion (55). The blowers can be powered by thermal-electric elements from the heat of the stove and thus do not require the house to be electrified. Behavioral innovations include designing biomass stoves to mimic the proven attractiveness and user satisfaction of gas stoves (197). New dissemination approaches have focused on market-based mechanisms in lieu of earlier purely government-subsidized efforts, but they also tap into the international carbon market for stove financing (199). All these approaches need to recognize that cooking is not a single process and that multiple devices and behavioral incentives to address stove "stacking" may be needed to reduce poor combustion sufficiently to reach health goals (181).

The evidence base for the potential benefits of stove improvements is growing. In simulation studies of the Indian National Cookstove Initiative, assuming successful adoption of low-emission stoves, Wilkinson et al. (225) projected approximate mortality reductions of 30% for pneumonia, 28% for COPD, and 6% for ischemic heart disease by 2020. A trial of chimney stoves in Guatemala found a 50% reduction in smoke exposures associated with an 18% reduction in physician-diagnosed child pneumonia (194). In households that achieved a 90% reduction in exposure, child pneumonia dropped by half—an improvement greater than that achieved by available vaccines and nutrition supplements, the other major interventions that can prevent this leading killer of children. Predictably, studies using poorly designed "improved" stoves, with no prior evidence of acceptance by the community or of pollution reduction, have found few benefits, low penetration, and/or inconsistent use by households (e.g., 77).

Three-fifths of the human population uses gas or electricity to cook all the world's cuisines; these fuels create little or no pollution in the kitchen. Thus, another approach to reducing the health burden of solid cooking fuels is to promote the use of these clean alternatives as widely as possible. This approach can be facilitated by making liquefied petroleum gas and natural gas more widely available through innovative business models and promoting, where possible, biogas made from animal dung and clean liquid fuels, such as ethanol made from sugar cane. Judicious dissemination of efficient electric cooking devices, such as rice cookers, also reduces the need for combustion in the house. Mounting evidence, however, shows that kerosene, which has been subsidized in many countries ostensibly to help the poor, poses a set of serious health risks (120) and should probably be eliminated over time, as Indonesia has done in a remarkably short period (170).

FOSSIL FUELS

The health impacts of fossil fuels occur across a life cycle, from mining to transport to combustion to waste management. Impacts manifest on spatial scales from local to global, both nearby and remotely, and both promptly and after substantial delay.

All fossil fuels contribute to global climate change because their combustion releases climate-altering pollutants, principally CO_2, methane, black carbon, and ozone precursors. The health impacts of climate change itself have been extensively reviewed (100, 137, 196) and are beyond the scope of this article.

Coal

Coal is a major energy source, constituting ~25% of energy consumption worldwide (21% in the United States) and 40% of electricity generation worldwide (45% in the United States) (65) (although its use is currently declining in favor of natural gas in some places). Coal accounts for ~40% of anthropogenic CO_2 emissions and is therefore a major contributor to climate change.

Coal can be produced through surface or underground mining—both dangerous operations for workers. The 1% of the global workforce engaged in mining accounts for 8% of fatal occupational injuries (~15,000 per year) (104), including some 3,800–6,000 annual premature deaths in China (47). Injuries occur from falling rocks, falls into mine shafts, misuse of machinery, gas inhalation, explosions, floods, and cave-ins (4). Respiratory exposures to silica dust and coal dust place miners at risk of silicosis and coal workers' pneumoconiosis (180). Miners also suffer an excess risk of lung cancer (41). Since 1900, more than 100,000 coal miners have been killed in mine incidents, and more than 200,000 have succumbed to coal workers' pneumoconiosis (47). Other occupational hazards include dangerous levels of heat and noise.

PM_{10}: particles less than 10 μm in diameter

The Global Burden of Disease estimates that nearly half a million premature deaths occurred in 2010 from occupational injuries worldwide, a large portion in mining.

Many modern coal mines involve mountaintop removal and strip mining, which result in ecological damage, stress nearby communities, increase the risk of mudslides, and contaminate water sources with waste emissions (87, 144, 158). One study found elevated rates of cardiovascular, pulmonary, and kidney diseases in West Virginia communities near coal-mining operations (83).

After being mined, coal is processed and transported to power stations, factories, and other points of use. Processing results in occupational hazards, including dust exposure (in such operations as forming briquettes for residential use), noise, ergonomic hazards (4), and carcinogen exposure (in converting coal to derivative fuels such as coke or coal gas). Coal gasification was widely used to produce fuel gas from coal during the nineteenth and early twentieth centuries; although no longer common, it left a legacy of more than 50,000 manufactured gas plants across the United States. These sites are commonly contaminated with aromatic organic compounds, metals, and other toxics, posing community health risks and high cleanup costs (80). About 70% of coal is transported by train, representing ∼44% of US train freight tonnage (6). Consequences of this freight traffic include noise and dust exposure, as well as injuries and fatalities from crashes and other incidents (totaling 709 fatalities in 2011) (51).

Combustion is the stage of the coal life cycle with the heaviest health burden (60). Primary products of coal combustion include CO_2, carbon monoxide, oxides of sulfur, oxides of nitrogen, a range of solid and vapor-phase organic compounds, PM, mercury, and other metals. Secondary pollutants—those formed in the air from precursors emitted from smokestacks—include ozone, some components of PM (sulfates, nitrates), and organic vapors. These exert their effects downwind from where the precursors are emitted, sometimes hundreds of miles away, as they form in moving air masses. All criteria pollutants are created by combusting coal.

CO_2 is the most significant pollutant in the context of climate change but has no direct human health effects at environmental levels. Many other pollutants from energy use exert health effects directly, however. Landmark episodes—in Belgium's Meuse River Valley in 1930, in Donora, Pennsylvania, in 1948, and in London in 1952—resulted from intensive coal combustion, with human exposure enhanced by local geography and weather. These episodes highlighted the acute fatal potential of coal combustion. Less dramatic effects, and less acute effects, have been intensively studied in recent years and are in many cases relatively well characterized (118).

PM—both coarser PM_{10} and finer $PM_{2.5}$—are epidemiologically associated with both acute and chronic mortality in urban areas, as well as with increases in hospitalizations and respiratory symptoms and decreases in lung function (224). Long-term studies in the United States (166, 167) and globally (82) have found strong associations between human exposure to fine PM and adverse impacts on human health, including lung cancer and premature deaths from cardiopulmonary disease (20). Because there is no well-defined safe threshold for PM exposure (186), incremental increases in PM concentration can increase rates of premature death in relatively clean communities as well as in polluted ones. Moreover, because of long-range atmospheric transport, imported PM can add significantly to disease burden. A recent evaluation of the global transport of fine aerosols attributed nearly 380,000 premature adult deaths in 2000 to PM originating in foreign continents (129). Populations at greatest risk include the elderly and those with preexisting cardiopulmonary disease. Not yet clear from the available evidence is which chemical components of PM are most relevant to health effects.

The burden of disease from PM is large. The 2010 Global Burden of Disease study estimated the global impact of $PM_{2.5}$ for four major causes: adult heart disease, stroke, lung cancer, and acute lower respiratory infections in children through age four. In 2010, PM resulted in 3.1 million premature deaths or ~3% of the total lost healthy life years in the world (126). Unlike HAP, not all outdoor PM air pollution is due to energy production and use. Nevertheless, energy use (including in households) probably accounts for more than 80% of ambient PM globally (175).

Coal accounts for most PM pollution in some cities, while biomass, diesel, road and construction dust, and other sources account for substantial portions in other cities. Reducing coal combustion can have substantial benefits. When Dublin eliminated household coal combustion in 1990, black smoke levels fell by about two-thirds, and cardiovascular and respiratory deaths dropped by 10% and 15%, respectively (30).

Ozone is photochemically produced by the catalytic reaction of NOx with CO, volatile organic compounds, and methane. Emissions of these precursors, from coal combustion and other sources, can contribute to ozone formation both near and far from where they are emitted. Ozone, in laboratory studies, can increase bronchial reactivity, inflame pulmonary tissues, and acutely and reversibly reduce lung function (113). Epidemiologic studies implicate ozone in worsened asthma, increased emergency room visits and increased hospital admissions (107), and increased mortality (101, 105, 147), even at low levels of exposure. Populations most at risk include children, the elderly, and people who are active outdoors, especially those with asthma. Investigators continue to find more health impacts from ozone (105), which will probably add to the 2010 Global Burden of Disease estimate that ozone accounted for less than 3% of the impact of outdoor particle pollution globally (126).

Mercury is a neurotoxin. Coal combustion is the largest source of anthropogenic mercury emissions globally, accounting for about half of such emissions, with emissions highest and growing in China and India (156, 164). Flue gas emission control technology can reduce mercury emissions, but this technology is uncommon in low- and middle-income countries (172).

Coal combustion waste (CCW), the final step in the coal life cycle, has received less attention in the health literature, but potential hazards were highlighted in December 2008, when more than one billion gallons of coal ash slurry spilled from a power plant impoundment near Kingston, Tennessee. CCW, including fly ash from smokestacks and bottom ash and boiler slag from furnaces, represents the second largest solid waste stream in the United States after municipal solid waste (146). Coal ash contains toxic metals such as arsenic, lead, mercury, cadmium, and chromium, as well as radioactivity (93). The US Environmental Protection Agency (EPA) has not yet regulated CCW as hazardous waste.

Studies of the health costs of coal-derived electricity have yielded estimates ranging from \$62 billion to \$523 billion annually, or from 3.2 cents to 28.9 cents per kWh—at the upper extreme, several times the current cost of electricity in the United States (47, 124, 148).

Petroleum

Petroleum is a liquid mixture of aliphatic and aromatic hydrocarbons. Petroleum, when refined, yields a variety of products, from lubricants to asphalt, but most—in the range of 85%—becomes fuel. Globally, petroleum accounts for 37% of primary energy consumption and more than 90% of transportation fuel—principally gasoline, diesel fuel, and jet fuel—but only 1% of electricity generation. When refined, a 42-gallon barrel of crude oil yields ~20 gallons of gasoline, nine gallons (combined) of diesel fuel and heating oil, three gallons of jet fuel, and smaller amounts of other products such as liquefied petroleum gas and propane, some of which goes to heating and power generation (65).

The petroleum life cycle begins with exploration, drilling, and extraction. Workplace hazards at this stage include injury risk, ergonomic hazards, noise, vibration, and chemical exposures (117). Offshore oil well work also entails long-term shift work (179). Large-scale spills during extraction, such as the 2010 Deepwater Horizon spill (38, 70, 204), and during transport by pipeline or ship, such as the 1989 Exxon Valdez spill (157) and the 1998 pipeline leak and subsequent explosion in northern Nigeria (5), can cause considerable ecological damage as well as human health impacts ranging from acute injuries and fatalities to food contamination and mental health disorders (1). In some places, such as Iraq, Colombia, and Nigeria, refineries and pipelines have been targets of intentional attacks, resulting in some of the same health impacts (152).

Petroleum refining entails extensive potential exposure to chemicals, many of them carcinogenic. A series of epidemiological studies of petroleum industry workers in the 1990s and 2000s revealed a strong healthy worker effect and few consistent patterns of illness (e.g., 205, 213) other than an excess of mesothelioma (114, 205); critics identified sources of negative bias (44). Communities near refineries are often also exposed to a range of air toxics (17).

Synthetic crude oil can be produced from oil sands or oil shale. These processes are somewhat more energy intensive than producing conventional petroleum, resulting in higher greenhouse gas emissions (26), and can cause considerable local ecological disruption (62). A review by the Royal Society of Canada, focusing on Alberta's extensive oil sands industry, found adverse health effects related to boomtown social disruption, such as violence and substance abuse, but no increase in cancer or other chemical-related outcomes (223).

As with coal, combustion of petroleum products yields a range of air pollutants, including CO_2, carbon monoxide, oxides of nitrogen and sulfur, hydrocarbons, PM, and metals; secondary ozone formation is also important (see discussion above about these pollutants). The major use of petroleum is as transportation fuel, and the health impacts of transportation-related emissions have been well studied (119). Data are also available on less common petroleum products, such as residual oil (used for heating buildings) (161, 162), a source of trace metal exposure (e.g., nickel). The solid waste remaining after petroleum product combustion, oil fly ash, may have health effects similar to those of conventional fly ash (61).

Ironically, a lack of petroleum may also exert health effects. Researchers have examined the health implications (58, 185) of "peak petroleum"—the concept that petroleum supplies are finite and costs and environmental damage will continue to rise as more remote, dilute, and difficult resources are tapped (21). Negative impacts may include reduced availability and increased costs of some foods, more costly medications and medical supplies, and transportation barriers; positive impacts may include a shift from motor vehicles to more active transportation.

Gas

Natural gas has become more important as technical advances—precision drilling of deep wells and hydraulic fracturing—have boosted production, to date most notably in the United States. Natural gas, which is mostly methane, has been considered a promising "bridge" energy source to eventual nonfossil sources because methane combustion generates about half the CO_2 per unit of energy released as does coal combustion. Life cycle analyses of natural gas production, especially from unconventional sources such as shale, however, suggest that the climate impact of this energy source (when accounting for methane leakage during production) may be far less advantageous than initially thought (91). In addition, leaked methane contributes to ozone formation with associated adverse health impacts. Other health concerns arise from hydraulic fracturing ("fracking"), which entails high-pressure injection of a mixture of water, sand, and chemicals into underground rock formations. Contamination of water tables, both by methane (153) and by fracking chemicals, is possible, although data on the magnitude of this problem are scarce to date (31, 53, 138).

NUCLEAR

Nuclear energy supplied ~11% of global electricity production in 2011. Three countries draw more than half their electricity from nuclear plants (France leads at 78%, followed by Slovakia and Belgium at 54% each), and ten additional countries, all but one in Europe, draw more than 25% from this source. In the United States, 19% of electricity comes from nuclear plants (220). A full description of the nuclear fuel cycle is beyond the scope of this review. Each step in nuclear energy production, from uranium mining to radioactive waste disposal (with reprocessing sometimes included), leads to radioactive and chemical emissions and waste streams.

For nuclear workers, the major occupational health concern is radiation-induced cancer (reviewed in 221). Among uranium miners, the main risk stems from exposure to radon gas in underground mines; various studies have documented significant excesses in lung cancer among these workers (e.g., 71, 143). Recent research suggests that exposure to ingested and inhaled uranium may be riskier than previously estimated, mainly because of the likely synergy between chemical carcinogenicity and radiation effects (216). Evidence also indicates that uranium may have endocrine-disrupting activity (173). The largest available study of nuclear power workers (more than 400,000 workers in 15 countries, contributing more than 5 million person-years of observation) found increased risks of solid cancers and leukemia (23), consistent with prior studies of low-dose radiation health effects (145).

Uranium mining, the first step in the nuclear power life cycle, generates large amounts of waste material (tailings and rock) and contaminated process water, which may contain low-level radioactivity, metals, and acids. These can cause considerable ecological damage. It may also threaten health by contaminating drinking water and food chains in nearby communities.

During normal operation, nuclear reactors routinely release radioactive gases to the atmosphere and radioactive liquids to the sea or rivers. In addition, when reactors are depressurized for refueling, larger gaseous emissions occur over short time periods. The main radioactive releases are tritium (half-life about 12 years), carbon-14 (5,700 years), krypton-85 (11 years), argon-41 (1.8 hours), and a number of iodine isotopes (including iodine-129, 16 million years). Emissions from reprocessing plants, which are found mostly in France and the United Kingdom, exceed those of power plants by several orders of magnitude. The resulting radiation doses, however, are a small fraction of those from natural or medical radiation exposures, when considered on a global scale (35).

The health consequences among populations living downwind of nuclear power plants remain controversial. In the 1990s, several studies found increases in the incidence of childhood leukemia near UK nuclear facilities. Official estimated doses from released nuclides were too low, however, by two to three orders of magnitude, to explain the increased leukemia. Recent epidemiological studies have reopened the child leukemia debate. A meta-analysis of 136 nuclear sites in Europe, North America, and Japan found a 5–24% elevation in childhood cancer mortality depending on proximity to nuclear facilities (8). The KiKK study (Kinderkrebs in der Umgebung von Kernkraftwerken, or Childhood Cancer in the Vicinity of Nuclear Power Plants) (109, 206) found a 60% increase in solid cancer risk and a 120% increase in leukemia risk among young children living within 5 km of German nuclear reactors. One hypothesis (48) proposes that infant leukemia is mainly a teratogenic effect of in utero radiation exposures due to maternal radionuclide intake during pregnancy. Whatever the explanation(s), recent epidemiological evidence suggests possible increased cancer rates among children living near nuclear reactors. Fortunately, cancer in children is a relatively rare occurrence in all societies.

The health risk of high-level waste relates to its high radiation levels. Although there is no example yet of such occurrences from nuclear fuel cycles, evidence from weapons production in the former Soviet Union shows that high-level wastes released into ground or surface water or rivers can enter food chains. The resulting individual exposures would likely be much smaller than a direct-exposure dose but could impact a far larger population than in the workplace. At present, no country has a strategy or facility for long-term disposal or storage of high-level radioactive waste, which reduces public and policy acceptability of this energy source.

Additional health risks relate to the possibility that plutonium or enriched uranium from nuclear power systems may be diverted to nuclear weapons production by rogue states or terrorists (24). In addition, nuclear power facilities may provide targets for terrorist attacks. The magnitude of these risks is difficult to quantify.

In addition to the routine risks of nuclear power, reactor accidents pose potentially significant health risks (28). Major nuclear power reactor accidents to date include those at Three Mile Island, United States, in 1979, Chernobyl, Ukraine, in 1986, and Fukushima, Japan, in 2011. Four types of radiation exposure may occur during and after a nuclear plant accident. First, plant workers or cleanup crews in close proximity to a radiation source may sustain total or partial body exposure. These doses may be quite high, to the point of acute fatality. Second, external contamination may occur when fission products settle on people's skin. Third, internal contamination may occur when people ingest or inhale fission products such as radioactive iodine and cesium isotopes—the mechanism of widespread population exposure. Iodine-131 tends to settle to the ground, enter the food chain, and accumulate in the thyroid, where it releases beta radiation, but only for a few weeks because of its short half-life (140). Large quantities of radioactive water were released into the ocean at Fukushima, and impacts mediated through the marine food chain have not been fully characterized.

The immediate death toll of nuclear accidents has been low. Radiation accounted for no fatalities at Three Mile Island or Fukushima and 28 fatalities among workers at Chernobyl (218). Physical trauma, heat stress, and related causes accounted for some acute fatalities among workers and community residents; although precise counts are unavailable, these probably numbered in the dozens following Chernobyl and Fukushima (209). Following Chernobyl, there were 134 confirmed cases of acute nonfatal radiation illness (98) among emergency workers.

Long-term outcomes have been studied after the Chernobyl and Three Mile Island accidents. International expert committees have analyzed Chernobyl health impacts (15, 98, 217) and found long-term impacts to be in the range of several thousand premature cancer deaths. For comparison, the exposed populations had a background occurrence of millions of cancer deaths and much larger natural radiation exposures over the same period. Nevertheless, the chaotic initial response, uncertainties in dose reconstruction, and incomplete health data collection have left many questions unanswered (13, 49, 86, 149, 183).

The Chernobyl accident resulted in the resettlement of 400,000 people from affected parts of Belarus, Russia, and Ukraine, with enormous social and economic consequences (163). Substantial mental health burdens have been documented among both those relocated and those remaining in contaminated areas (18, 19, 86), including poor self-rated health, anxiety, depression, and other symptoms of posttraumatic stress disorder (PTSD). Cleanup workers demonstrated substantial increases in suicide, suicidal ideation, PTSD, and other psychiatric illnesses, which persisted two decades after the accident (19, 130, 171). Researchers found that general psychological distress was also common in nuclear plant workers in the months after the Fukushima disaster. Evidence of neuropsychiatric impacts on exposed children is inconsistent (19). Following the Three Mile Island disaster, similar mental health consequences were documented (10, 37).

Nuclear energy garners considerable public and policy concern. The main public health effect of routine nuclear plant operation identified to date is a possible increased incidence of childhood leukemia. The main burden of disease following nuclear accidents has been thyroid cancer and mental health impacts in exposed populations, with additional impacts on cleanup workers. Further concerns include the local effects of uranium mining and milling and the management of nuclear waste. The potential for weaponization or terrorist attacks on nuclear fuel cycle facilities, however, pose the most difficult, yet perhaps the largest, risks to quantify and manage (220).

EMERGING/RENEWABLE

Renewable sources of energy offer several potential advantages. They do not irreversibly deplete finite resources, and most have a lower climate footprint than do fossil fuels. If managed well, they can pose minimal health risks and can yield social and economic cobenefits. Whether the benefits are realized depends strongly on how renewable energy is produced. No energy source is free of health and environmental impacts. Issues of land use, maintenance, materials inputs, and energy storage raise concerns about environmental, occupational, and community health impacts.

Solar

Three technologies are used to generate electricity from solar radiation: photovoltaic (PV) cells, which generate electricity directly; concentrating solar power thermal systems, which use a liquid to transfer absorbed heat to a steam generator that drives a turbine; and solar towers, which are effectively chimneys in which rising hot air powers turbine generators. Solar energy technologies have been deployed in both small-scale (mainly rooftop) applications and in large-scale electrical production.

The major health concern from solar power relates to the life cycle of PV cells. These are typically made with crystalline silicon and, depending on the technology used, include compounds such as copper indium diselenide (CIS), copper indium gallium diselenide (CGS), gallium arsenide (GaAs), and cadmium telluride (CdTe). Silica mining is associated with risk of silicosis, a type of pneumoconiosis (123). PV manufacturing, like semiconductor manufacturing, may entail exposure to toxic metals (cadmium, arsenic, chromium, and lead) and gases (arsine, phosphine, and silane) (59, 210). Little information is available on workplace exposures; available data suggest that environmental emissions are generally low (59), although waste management and end-of-life product disposal remain challenges (191). Overall the health impact of solar power is likely to be far less than that of any of the fossil fuels.

Biofuels

Biofuels are derived from recently formed biomass (as opposed to the ancient biomass that comprises fossil fuels). Ethanol and biodiesel, the two principal modern biofuels, are primarily liquid transportation fuels. First-generation biofuels such as ethanol are made from food crops, including grain, sugar beets, and sugarcane, and blended with petroleum-based gasoline. Biodiesel is made from vegetable or animal fats; it is used either in pure form or as a blend with conventional diesel fuel. Second-generation biofuels, which are under development, will draw on a broader range of plant and nonfood sources, such as crop residues, switch grass, and algae, and will use advanced production processes. The aims are to spare the use of food crops—lowering global food prices and promoting nutrition—spare productive farmland, reduce fossil fuel and water use, and protect water quality and wildlife habitat. Global biofuel production grew from 16 billion liters in 2000 to more than 100 billion liters in 2011, supplying ~1.5% of global transportation fuel. Some countries rely heavily on biofuels. For example, 23% of Brazil's transportation fuel is biofuel; the United States has reached 10% ethanol in light-duty vehicles (214) and may achieve 15–17% by 2030 (43). Subsidies and other policy incentives have supported the growth of the biofuel industry. However, the drought-associated fall in the

US corn crop in 2011 and 2012 has stimulated calls to reduce the diversion of corn to ethanol.

A claimed principal potential health benefit of biofuels is reduction of greenhouse gas emissions relative to fossil fuel use (52, 84). However, recent life cycle analyses that account for fossil fuel inputs, land use changes, and other factors suggest that the climate advantage of many biofuels may be marginal (43, 121, 187, 189) (**Figure 4**). Second-generation biofuels may increase the climate benefits (90). A second potential health benefit of biofuel is reduced air pollution, both at the tailpipe and throughout the life cycle—a benefit documented for both ethanol [from cellulose if not from corn (85)] and biodiesel (134, 139), although with variable results. Biodiesel vehicles, in particular, have substantially lower emissions of PM, carbon monoxide, volatile organic compounds, and oxides of sulfur, compared with conventional diesel vehicles (139).

These benefits could be offset by the other potential health and environmental costs, however. One issue is the diversion of farmland to grow biofuel feedstock instead of food, the so-called "food versus fuel" dilemma (178), with rising food prices that may threaten the nutritional status of at-risk populations (182). Food prices are determined by a complex web of causal factors, however, and debate remains about the role of biofuels (7, 33, 141). Biofuel production may also result in freshwater depletion, water pollution, and loss of forest, wildlife habitat, and ecosystem services (36, 43, 50), and even such indirect unforeseen consequences as increasing antibiotic resistance (150). Occupational health threats in the biofuel industry have not been well studied, but evidence from a Danish study shows elevated worker exposure to dust, endotoxin, fungi, and aspergillus (184). Optimizing biofuel use, including health benefits, will require careful life cycle analyses, development of efficient crops and production technologies, use of crop waste and marginal rather than productive agricultural land to the extent possible, more attention to health impacts (176), and policies that advance these goals (27, 178).

Hydroelectric

Hydroelectric power is produced when falling or flowing water strikes the blades of turbines, which, in turn, generate electricity. Units range from very large, such as China's Three Gorges Dam, which will generate ~22,500 MW when complete, to very small, generating 10 kW or less—enough to power individual homes, farms, or small villages. Larger hydroelectric plants typically feature dams that form reservoirs. Dams often provide other benefits in addition to electric power generation, including flood control; water storage for household, industrial, and agricultural use during droughts; irrigation; and recreational opportunities. Hydroelectric power represents 16% of the world's electricity supply (46), and about 1 in 4 of the world's 36,000 registered dams are used for hydropower generation (99).

Hydroelectric generation is widely considered a clean source of energy because it does not involve combustion. Environmental impacts on river systems can be significant, however, especially with large dams (116). These include altered water flow, temperature, and sedimentation, reduced water quality, loss of wetlands, disruption of fish migration, and even species extinction (69). Large hydroelectric facilities, especially in warm climates, may also contribute to greenhouse gas emissions (45) owing to decomposition of organic matter following flooding, leading to the release of CO_2 and methane (42).

Direct health impacts of hydropower fall into three categories: population displacement, infectious disease risk, and disaster risk related to dam failures.

Population displacement. The construction of large dams has caused considerable involuntary displacement of the populations that reside in areas to be flooded (230). Often, these are vulnerable populations, subject not only to forced displacement but to numerous social and health burdens. A large literature has analyzed the social and health impacts of dam construction and resulting displacement

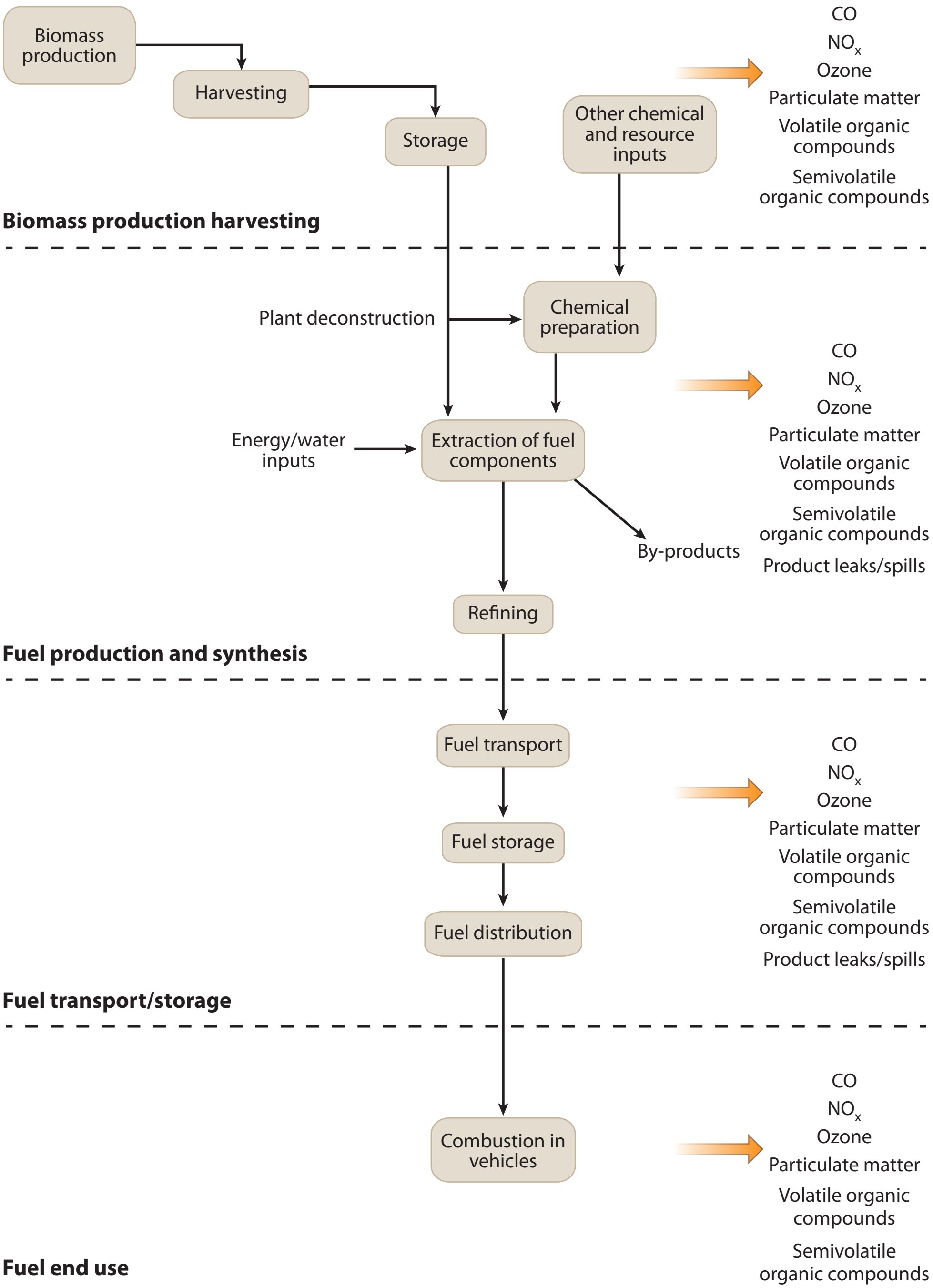

Figure 4

Life cycle analysis. Example of pollutants associated with biofuel production, transport, and use. From Reference 196, figure 4.13.

(54, 136). Construction of China's Three Gorges Dam, for example, completely or partially flooded 13 cities and towns, 365 townships, and 1,711 villages, inundated about 26,000 hectares of farmland, and displaced at least 1.3 million residents (94). Studies showed resulting impoverishment, collapse of social support networks, homelessness, and unemployment, and such health impacts as depression and poor self-rated health (95, 233).

Infectious diseases. Hydroelectric projects, by altering local hydrology and expanding the habitat of infectious organisms and/or vectors, can increase the risk of certain infectious diseases (108). The best-studied diseases in this regard are schistosomiasis and malaria.

Dam construction can promote schistosomiasis by expanding the snail vector's habitat (in the aquatic weeds that flourish in reservoirs), prolonging the breeding periods (functionally eliminating the dry season that would otherwise reduce snail populations), and prolonging human contact with wet environments and therefore with snails. Steinmann et al. (207) pooled data from studies in Nigeria, Mali, Cameroon, Côte d'Ivoire, Democratic Republic of the Congo, and Ethiopia. They found that living near a dam reservoir in endemic areas is associated with more than a doubling of risk (relative risk 2.4 for *Schistosoma haematobium*, and 2.6 for *S. mansoni*). The Three Gorges Dam is expected to increase the risk of schistosomiasis in some areas, although the risk may decrease in other areas and control programs may mitigate some of the risk (125, 188, 237).

Malaria risk has been well studied in connection with irrigation projects, but less so in connection with hydroelectric dams, perhaps because relatively few such dams are located in malaria-endemic areas (110). Some studies have shown no impact of hydroelectric dam construction on nearby malaria (68), but most show an increase in risk (112, 122, 234).

Dam failures. Dam failures may occur because of poor construction, military or terrorist attack, earthquakes, or other causes. These can be catastrophic to downstream communities. Several examples illustrate the magnitude of the disasters that may result and the cost in lives. In May 1943, Allied bombing of dams on the Möhne and Ruhr rivers in Germany (Operation Chastise) resulted in more than 1,000 deaths in flooded downstream areas. In 1963, the Vajont Dam north of Florence, Italy, overtopped owing to an upstream landslide. Several downstream villages were destroyed, killing ~2,000 people. In 1975, torrential rainfall during a typhoon caused the failure of the Banqiao Dam in Henan Province, China, together with other smaller dams; an estimated 171,000 people were killed and 11 million lost their homes. However, dams have reduced periodic floods in some areas, including China, where Yangtze River floods have killed millions over the centuries.

Policy on dams needs to balance the considerable health benefits of available energy and water management with local adverse health and social impacts (127, 131, 230). For this purpose, guidelines have been issued for equitable, atraumatic resettlement (229).

Wind

Wind power provides a small but growing segment of electrical energy, reaching 2.9% in the United States by 2011 and between 2% and 3% globally (with higher proportions in some countries, such as nearly 26% in Denmark, 16% in Spain and Portugal, and 12% in Ireland) (174). Wind has the potential to supply a significant portion of world energy needs (236). Health benefits of wind power include the absence of greenhouse gas and other pollutant emissions during operation (although some emissions are associated with manufacturing the equipment), as well as the absence of a routine waste stream.

Health concerns center on the swishing, whistling, or throbbing noise from moving gear trains and turbine blades (78, 79). Some studies have found self-reported annoyance, sleep disturbance, and reduced quality of life among people who live near wind turbines, especially those who can see the turbines and/or who dislike them (102, 159, 160, 190). Protective strategies involve noise reduction and increased distance between wind turbines and people. Overall, the population health impacts appear to be far lower than for equivalent energy generation by fossil fuel combustion (25, 32, 115).

ENERGY EFFICIENCY, CONSERVATION, AND COBENEFITS

Energy conservation refers to reducing the use of energy. This goal may be achieved by reducing energy demand and/or through energy efficiency—obtaining more service from each unit of energy used.

Reduced energy use may offset forms of energy production with adverse health effects. For instance, reducing demands on coal-fired power plants, all things being equal, should lower fuel cycle risks, reduce atmospheric emissions of pollutants, limit demands on infrastructure, lower costs, and contribute to economic competitiveness. Simply put, conservation is an efficient, economical, healthful, and environmentally friendly approach to energy use.

Two major caveats apply. First, ∼2.8 billion people lack access to clean fuels for cooking, and ∼1.6 billion people lack access to electricity (155). For these people, as for impoverished people in wealthy nations who cannot afford heating or air conditioning, adequate access to clean energy is a more pressing health need than is energy conservation (although energy-efficiency improvements will often lower overall energy costs). Second, energy efficiency may have paradoxical health effects, such as increasing overall consumer demand for energy—the so-called "take back" effect (193). Therefore, although it is always a good idea to reduce the energy required for human well-being, estimating the net impacts of energy conservation requires thorough analysis.

The health benefits of conservation (especially for high-income populations) have been studied best in the context of reducing emissions of climate-altering pollutants, a pillar of climate change mitigation. Haines et al. (76) identified five major opportunities for energy efficiency and conservation to advance climate change mitigation as well as environmental, health, and development goals: (*a*) economy-wide carbon-intensity reduction, (*b*) use of more efficient vehicles, (*c*) reduced use of vehicles, (*d*) efficient buildings, and (*e*) efficient base load coal plants. Researchers have calculated health benefits of climate change mitigation, often denoted "cobenefits," for several of these conservation strategies (see following section).

Energy Generation and Transmission

Published analyses of health benefits generally focus on reduced coal combustion (achieved through, say, carbon taxes) and/or greater efficiency in coal-fired power plants or in the distribution grid (reviewed in 14, 199, 219). Investigators have conducted analyses in various parts of the world, including Europe (132), India (132), Latin America (29), and China (22, 219). Results generally show a considerable savings in lives, from both acute and chronic mortality, with reduced and/or more efficient coal combustion. For instance, Vennemo et al. (219) estimated between 34 and 161 fewer premature deaths in China per million tons of CO_2 emission reduction. Results are sensitive to assumptions regarding population density and proximity to coal-fired power plants, concurrent risk factors, quality of the coal used, and other factors.

Transportation

The second and third opportunities identified by Haines et al. (76) relate to transportation, including both greater vehicle efficiency and reduced vehicle use. Researchers have modeled the health benefits of efficient vehicles; these benefits reflect both greater fuel efficiency and lower emission rates. For example, an American Lung Association of California study (2) projected the health benefits of full implementation of California's Advanced Clean

Car Standards, which include both energy efficiency and emissions reductions. Projected annual benefits to California's population of 37.7 million include 400–420 avoided premature deaths, 8,075–8,440 avoided asthma attacks and cases of lower respiratory symptoms, 390–405 avoided heart attacks, and $7.2–8.1 billion in avoided health care costs. Woodcock et al. (228) considered lower-emission motor vehicles, improved fuels, and certain information and communication technologies to reduce emissions in two cities: London and Delhi. Health benefits, reflecting reduced PM emissions, amounted to 74 fewer premature deaths and 1,696 life-years saved in Delhi and 17 fewer premature deaths and 160 life-years saved in London, per million people per year. When efficiency strategies include smaller vehicles, a trade-off results: Vehicular crashes result in more severe injuries (96).

Reduced vehicle use may reflect lower travel demand, mode shifting from motor vehicles to active transport (walking and cycling) (64, 177, 227), or both, with concomitant redesign of the built environment (235). Conserving energy by reducing automobile travel (in effect substituting human exertion for vehicular engines as the energy source) has a range of health cobenefits related to improved air quality, increased physical activity, reduced car crashes, and reduced noise. For example, in a study of short-term traffic-volume reduction during the 1996 Atlanta Olympic Games, lower peak daily ozone concentrations (by 27.9%) were associated with fewer asthma acute care events (decreases from 11.1% to 44.1% across various clinical settings) (56).

Several studies have explicitly calculated the health benefits of shifting from automobile travel to cycling. Woodcock et al. (228), in their study of London and Delhi, posited a doubling of walking and an eightfold increase in cycling in London to levels common in some European cities, whereas in Delhi they posited a small increase in walking, more than a doubling of cycling, and a large increase in transit use. In both cities, increased physical activity was projected to result in substantial decreases in dementia, cardiovascular disease, diabetes, depression, and breast and colon cancers—352 fewer premature deaths and 6,040 life-years saved in Delhi and 528 fewer premature deaths and 5,496 life-years saved in London, per million people per year. Decreased motor vehicle injuries and fatalities provided additional benefit, especially in Delhi. A follow-up analysis, applying similar assumptions across England and Wales, projected £17 billion savings in health care costs over 20 years, reaching nearly 1% of the National Health Service budget by 2030 (103). Lindsay et al. (128) modeled varying proportional shifts of short trips from cars to active transport in New Zealand's urban areas, a combined population of 2.7 million people. They found substantial energy savings and substantial reductions in all-cause mortality; a 30% mode shift yielded 716 fewer premature deaths each year (slightly offset by increased fatalities from cycling injuries).

Buildings

The fourth energy-efficiency strategy proposed by Haines et al. (76) is increased building energy efficiency—a promising approach because buildings account for a substantial proportion of energy use. Design features of energy-efficient buildings may include advanced heating and cooling systems; "tight" construction, including high-performing insulation, to reduce outside air exchanges and attendant energy loss; highly efficient appliances, lights, and other equipment; "smart" infrastructure that turns off lights, heat, and appliances when not in use; green roofs, shades, and other features to prevent overheating in hot weather; and other strategies (111). Reduced use of energy in buildings offers upstream health benefits, such as less coal combustion, and immediate benefits, such as enhanced well-being and protection from winter cold (63, 225). However, tight buildings may bring the unintended consequence of reduced air circulation and accumulation of moisture, mold, radon, volatile indoor compounds, and other indoor contaminants (196). In the tightest buildings, these problems can be alleviated by mechanical ventilation and heat recovery systems, which allow greater ventilation while remaining efficient by recovering heat from the vented air (225).

Cobenefits

Increasing energy efficiency across various sectors offers two types of cobenefits for health: mitigating climate change, by reducing emissions of climate-altering pollutants such as CO_2, methane, and black carbon; and also improving local health.[2] Other potentially important energy-related cobenefit opportunities include improving household combustion among the world's poor (199, 225) and reducing energy use associated with transport and other sectors (222). Another major source of cobenefits is to provide access to reproductive services to a larger portion of the world's women, which would reduce population growth and consequent energy demand and climate impact, while also reducing child and maternal mortality through spacing of births in high-fertility populations (151, 195).

CONCLUSIONS

The largest health impacts of today's energy systems come from the extraction and combustion of the solid fuels: biomass and coal. Two-fifths of humanity is exposed to household air pollution from the poor combustion of solid fuels used for household heating and cooking. In addition, virtually everyone around the world is exposed to some level of outdoor air pollution resulting from fuel combustion. These ambient emissions are largest for biomass and coal but also come from other fossil fuels, particularly petroleum fuels. Per unit of useful energy, the health benefits of emission-reduction interventions rise with proximity of combustion to people (i.e., as the intake fraction rises) and with the fraction of incomplete combustion. Accordingly, considering the widespread use of solid fuels in households, large cobenefit opportunities for health and climate lie in shifting away from solid fuels and dramatically increasing combustion efficiency in households.

Human-engendered climate change, which is largely but not entirely caused by energy use, is already imposing health impacts, particularly among poor populations. Health impacts from climate change can be expected to grow steadily in the next decades. Major mitigation and adaptation efforts can reduce the magnitude of future impacts. For long-term climate protection, CO_2 emissions need to be reduced drastically through energy-efficiency measures and a shift away from fossil fuels, although reducing other climate-altering pollutants from energy use, such as methane, black carbon, and ozone precursors, through fuel switching and better combustion, are also important for slowing the rate of warming. These non-CO_2 climate-altering pollutants directly damage health as well, so reducing their emissions yields substantial near-term cobenefits. Shifting urban design to promote more fuel-efficient transport modes also offers health benefits by increasing physical activity and reducing motor vehicle crashes and noise exposure.

Other energy sources, such as nuclear, carry some risk as well, although a quantitative comparison to the major energy risks is difficult because of the potential for low-probability, high-consequence disasters. Health impacts from most new and renewable energy sources are likely to be much smaller, but vigilance is needed to be sure these energy sources are managed carefully. Energy-efficiency measures are generally desirable, although care is needed to avoid potential health impacts that may result from reduced air exchange in buildings.

A life cycle approach to evaluating energy sources is important to understand fully the health and climate costs and benefits across production, storage, transport, and end-use processes. This approach enables both "full cost" and "full benefit" accounting (148)

---

[2] See the six-paper section in *Lancet* on cobenefits entitled, "Series on the Impact on Public Health of Strategies to Reduce Greenhouse Gases" (57, 75, 132, 200, 225, 228).

and permits identification and assessment of trade-offs. This process is essential because energy policy entails numerous trade-offs, many with direct human consequences. Multidisciplinary approaches are needed, and methods such as health impact assessments may be useful.

Although energy is essential to human well-being, energy systems contribute substantially to the global burden of disease. According to the Global Burden of Disease 2010 study, HAP from solid fuels was responsible for ~3.5 million premature deaths in 2010, and general outdoor air pollution, which has a large energy component, was responsible for ~3.1 million premature deaths in the same year (126). Particularly in Asia, a significant proportion of outdoor air pollution comes from poor household fuel combustion, indicating that globally about half a million of the premature deaths attributed to outdoor air pollution stem from pollution contributed by households. Inclusion of energy's indirect role in lead pollution and occupational risks would probably add another 10–20% to these figures, and inclusion of road traffic accidents and energy's role in physical inactivity would roughly double these values. Given the uncertainties of such calculations, the direct effects of energy systems alone exceed the global health impact of most other risk factors except malnutrition, rivaling the global impacts of tobacco, alcohol, and high blood pressure. The vast part of the direct impact comes from the poor management of fuel combustion. Clearly, energy is a global health issue.[3]

DISCLOSURE STATEMENT

H. Frumkin is a board member of the US Green Building Council. C. Butler is a member of the advocacy group Doctors for the Environment, Australia. All other authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

ACKNOWLEDGMENTS

This review was shortened, adapted, and updated from "Energy and Health," by K.R. Smith, K. Balakrishnan, C. Butler, Z. Chafe, I. Fairlie, P. Kinney, T. Kjellstrom, D.L. Mauzerall, T. McKone, A. McMichael, M. Schneider, and P. Wilkinson, the fourth chapter in *Global Energy Assessment: Toward a Sustainable Future*, by the Global Energy Assessment Writing Team, published by Cambridge University Press and the International Institute for Applied Systems Analysis, Cambridge, UK, 2012.

LITERATURE CITED

1. Aguilera F, Méndez J, Pásaro E, Laffon B. 2010. Review on the effects of exposure to spilled oils on human health. *Appl. Toxicol.* 30:291–301
2. Am. Lung Assoc. Calif. 2011. *The Road to Clean Air Study*. Oakland: Am. Lung Assoc. Calif. **http://www.lung.org/associations/states/california/assets/pdfs/advocacy/clean-cars-campaign/the-road-to-clean-air.pdf**
3. Armendáriz-Arnez C, Edwards RD, Johnson M, Rosas IA, Espinosa F, Masera OR. 2010. Indoor particle size distributions in homes with open fires and improved Patsari cook stoves. *Atmos. Environ.* 44:2881–86
4. Armstrong J, Menon R. 1998. Mining and quarrying. See Ref. 208, 3:74.1–55

---

[3] The extensively revised results of the Global Burden of Disease Project and Comparative Risk Assessment provide authoritative updated estimates of the health impacts of household air pollution, outdoor air pollution, and other energy-related risk factors globally and by region (126).

5. Aroh KN, Ubong IU, Eze CL, Harry IM, Umo-Otong JC, Gobo AE. 2010. Oil spill incidents and pipeline vandalization in Nigeria: impact on public health and negation to attainment of Millennium Development Goal: the Ishiagu example. *Disaster Prev. Manag.* 19:70–87
6. Assoc. Am. Railr. 2011. *Railroads and Coal.* Washington, DC: AAR
7. Babcock BA. 2011. *The Impact of US Biofuel Policies on Agricultural Price Levels and Volatility*. Geneva: ICTSD. **http://ictsd.org/downloads/2011/12/the-impact-of-us-biofuel-policies-on-agricultural-price-levels-and-volatility.pdf**
8. Baker PJ, Hoel DG. 2007. Meta-analysis of standardized incidence and mortality rates of childhood leukaemia in proximity to nuclear facilities. *Eur. J. Cancer Care* 16:355–63
9. Balakrishnan K. 2012. *Global Household Air Pollution Database: indoor concentrations and exposures from cooking fuels*. Version 2.0. Univ. Calif., Berkeley/Sri Ramachandra Univ., Porur, India/World Health Organ., Geneva. **http://www.who.int/indoorair/health_impacts/databases_iap/en/**
10. Baum A, Gatchel R, Schaeffer M. 1983. Emotional, behavioral, and physiological effects of chronic stress at Three Mile Island. *J. Consult. Clin. Psychol.* 51:565–72
11. Baumgartner J, Schauer JJ, Ezzati M, Lu L, Cheng C, et al. 2011. Indoor air pollution and blood pressure in adult women living in rural China. *Environ. Health Perspect.* 119:1390–95
12. Baumgartner J, Smith KR, Chockalingam A. 2012. Reducing CVD through improvements in household energy: implications for policy-relevant research. *Glob. Heart* 7:243–47
13. Baverstock K, Williams D. 2006. The Chernobyl accident 20 years on: an assessment of the health consequences and the international response. *Environ. Health Perspect.* 114:1312–17
14. Bell ML, Davis DL, Cifuentes LA, Krupnick AJ, Morgenstern RD, Thurston GD. 2008. Ancillary human health benefits of improved air quality resulting from climate change mitigation. *Environ. Health* 7:41
15. Bennett B, Repacholi M, Carr Z, eds. 2006. *Health Effects of the Chernobyl Accident and Special Health Care Programmes. Report of the UN Chernobyl Forum Expert Group "Health."* Geneva: WHO. **http://www.who.int/ionizing_radiation/chernobyl/WHO%20Report%20on%20Chernobyl%20Health%20Effects%20July%2006.pdf**
16. Boardman B. 2010. *Fixing Fuel Poverty: Challenges and Solutions*. London: Earthscan
17. Brody JG, Morello-Frosch R, Zota A, Brown P, Pérez C, Rudel RA. 2009. Linking exposure assessment science with policy objectives for environmental justice and breast cancer advocacy: the Northern California household exposure study. *Am. J. Public Health* 99(Suppl. 3):S600–9
18. Bromet E. 2012. Mental health consequences of the Chernobyl disaster. *J. Radiol. Prot.* 32:N71–75
19. Bromet E, Havenaar J, Guey L. 2011. A 25 year retrospective review of the psychological consequences of the Chernobyl accident. *Clin. Oncol.* 23:297–305
20. Brook RD, Rajagopalan S, Pope CA 3rd. 2010. Particulate matter air pollution and cardiovascular disease: an update to the scientific statement from the American Heart Association. *Circulation* 121:2331–78
21. Campbell C, Laherrère J. 1998. The end of cheap oil. *Sci. Am.* 278:78–83
22. Cao G, Zhang X, Zheng F. 2006. Inventory of black carbon and organic carbon emissions from China. *Atmos. Environ.* 40:6516–27
23. Cardis E, Vrijheid M, Gilbert E. 2005. Risk of cancer after low doses of ionising radiation: retrospective cohort study in 15 countries. *BMJ* 331:77–81
24. Case SR. 2011. *Proliferation Risk in Nuclear Fuel Cycles: Workshop Summary*. Washington, DC: Natl. Resour. Counc., Nucl. Radiat. Stud. Board
25. Chapman S. 2012. Editorial ignored 17 reviews on wind turbines and health. *BMJ* 344:e3366
26. Charpentier A, Bergerson J, MacLean H. 2009. Understanding the Canadian oil sands industry's greenhouse gas emissions. *Environ. Res. Lett.* 4:014005
27. Childs B, Bradley R. 2007. *Plants at the Pump: Biofuels, Climate Change, and Sustainability*. Washington, DC: World Resour. Inst.
28. Christodouleas JP, Forrest RD, Ainsley CG, Tochner Z, Hahn SM, Glatstein E. 2011. Short-term and long-term health risks of nuclear-power-plant accidents. *N. Engl. J. Med.* 364:2334–41
29. Cifuentes L, Borja-Aburto VH, Gouveia N, Thurston G, Davis DL. 2001. Climate change: hidden health benefits of greenhouse gas mitigation. *Science* 293:1257–59
30. Clancy L, Goodman P, Sinclair H, Dockery DW. 2002. Effect of air-pollution control on death rates in Dublin, Ireland: an intervention study. *Lancet* 360:1210–14

31. Colburn T, Kwiatkowski C, Schultz K, Bachran M. 2011. Natural gas operations from a public health perspective. *Hum. Ecol. Risk Assess.* 17:1039–56
32. Colby WD, Dobie R, Leventhall G, Lipscomb DM, McCunney RJ, et al. 2009. *Wind Turbine Sound and Health Effects: An Expert Panel Review*. Washington, DC: Am. Wind Energy Assoc./Ottawa: Can. Wind Energy Assoc. **http://www.awea.org/learnabout/publications/loader.cfm?csModule=security/getfile&PageID=5728**
33. Congr. Budg. Off. 2009. *The Impact of Ethanol Use on Food Prices and Greenhouse-Gas Emissions.* Washington, DC: Congr. Budg. Off. **http://www.cbo.gov/sites/default/files/cbofiles/ftpdocs/100xx/doc10057/04-08-ethanol.pdf**
34. Cook JT, Frank DA, Casey PH, Rose-Jacobs R, Black MM, et al. 2008. A brief indicator of household energy security: associations with food security, child health, and child development in US infants and toddlers. *Pediatrics* 122:e867–75
35. Cullings HM, Smith KR. 2010. Better radiation exposure estimation for the Japanese atomic-bomb survivors enables us to better protect people from radiation today. *J. Expo. Sci. Environ. Epidemiol.* 20:575–76
36. Demirbas A. 2009. Political, economic and environmental impacts of biofuels: a review. *Appl. Energy* 86:S108–17
37. Dew M, Bromet E. 1993. Predictors of temporal patterns of psychiatric distress during 10 years following the nuclear accident at Three Mile Island. *Soc. Psychiatry Psychiatr. Epidemiol.* 28:49–55
38. Diaz J. 2011. The legacy of the Gulf oil spill: analyzing acute public health effects and predicting chronic ones in Louisiana. *Am. J. Disaster Med.* 6:5–22
39. Dionisio KL, Howie S, Fornace KM, Chimah O, Adegbola RA, Ezzati M. 2008. Measuring the exposure of infants and children to indoor air pollution from biomass fuels in The Gambia. *Indoor Air* 18:317–27
40. Dix-Cooper L, Eskenazi B, Romero C, Balmes J, Smith KR. 2012. Neurodevelopmental performance among school age children in rural Guatemala is associated with prenatal and postnatal exposure to carbon monoxide, a marker for exposure to woodsmoke. *Neurotoxicology* 33:246–54
41. Donoghue AM. 2004. Occupational health hazards in mining: an overview. *Occup. Med.* 54:283–89
42. Duchemin E, Lucotte M, Canuel R, Chamberland A. 1995. Production of the greenhouse gases CH_4 and CO_2 by hydroelectric reservoirs of the boreal region. *Glob. Biogeochem. Cycles* 9:529–40
43. Earley J, McKeown A. 2009. *Red, White, and Green: Transforming U.S. Biofuels.* Worldwatch Rep. 180. Washington, DC: Worldwatch Inst. **http://www.worldwatch.org/files/pdf/Transforming%20US%20Biofuels.pdf**
44. Egilman D, Kol L, Hegg L, Bohme S. 2007. Manipulated data in Shell's benzene historical exposure study. *Int. J. Occup. Environ. Health* 13:222–32
45. Electr. Power Res. Inst. (EPRI). 2010. *The Role of Hydropower Reservoirs in Greenhouse Gas Emissions.* Palo Alto, CA: EPRI. **http://my.epri.com/portal/server.pt?Abstract_id = 000000000001017971**
46. Energy Inf. Adm. 2011. *International Energy Outlook 2011.* DOE/EIA-0484. Washington, DC: EIA. **http://www.eia.gov/forecasts/ieo/pdf/0484(2011).pdf**
47. Epstein PR, Buonocore JJ, Eckerle K, Hendryx M, Stout Iii BM, et al. 2011. Full cost accounting for the life cycle of coal. *Ann. N. Y. Acad. Sci.* 1219:73–98
48. Fairlie I. 2009. Childhood cancers near German nuclear power stations: hypothesis to explain the cancer increases. *Med. Confl. Surviv.* 25:206–20
49. Fairlie I, Sumner D. 2006. *The Other Report on Chernobyl (TORCH)*. Berlin/Brussels/Kiev: The Greens/EFA Eur. Parliam. **http://www.chernobylreport.org/?p=summary**
50. Fargione J, Hill J, Tilman D, Polasky S, Hawthorne P. 2008. Land clearing and the biofuel carbon debt. *Science* 319:1235–38
51. Fed. Railroad Adm., Off. Saf. Anal. 2012. *Accident/Incident Overview, Railroad-All/January to December, 2011.* Washington, DC: FRA
52. Field CB, Campbell JE, Lobell DB. 2008. Biomass energy: the scale of the potential resource.*Trends Ecol. Evol.* 23:65–72
53. Finkel ML, Law A. 2011. The rush to drill for natural gas: a public health cautionary tale. *Am. J. Public Health* 101:784–85

54. Finley-Brook M, Thomas C. 2010. From malignant neglect to extreme intervention: treatment of displaced indigenous populations in two large hydro projects in Panama. *Water Altern.* 3:269–90
55. Foell W, Pachauri S, Spreng D, Zerriffi H. 2011. Household cooking fuels and technologies in developing countries. *Energy Policy* 39:7487–96
56. Friedman MS, Powell KE, Hutwagner L, Graham LM, Teague WG. 2001. Impact of changes in transportation and communting behaviors during the 1996 Summer Olympic Games in Atlanta on air quality and childhood asthma. *JAMA* 285:897–905
57. Friel S, Dangour AD, Garnett T, Lock K, Chalabi Z, et al. 2009. Public health benefits of strategies to reduce greenhouse-gas emissions: food and agriculture. *Lancet* 374:2016–25
58. Frumkin H, Hess J, Vindigni S. 2009. Energy and public health: the challenge of peak petroleum. *Public Health Rep.* 124:5–19
59. Fthenakis VM, Kim HC, Alsema E. 2008. Emissions from photovoltaic life cycles. *Environ. Sci. Technol.* 42:2168–74
60. Gaffney JS, Marley NA. 2009. The impacts of combustion emissions on air quality and climate – from coal to biofuels and beyond. *Atmos. Environ.* 43:23–36
61. Ghio AJ, Silbajoris R, Carson JL, Samet JM. 2002. Biologic effects of oil fly ash. *Environ. Health Perspect.* 110:89–94
62. Giesy JP, Anderson JC, Wiseman SB. 2010. Alberta oil sands development. *Proc. Natl. Acad. Sci. USA* 107:951–52
63. Gilbertson J, Stevens M, Stiell B, Thorogood N, Warm Front Stud. Group. 2006. Home is where the hearth is: grant recipients' views of England's home energy efficiency scheme (Warm Front). *Soc. Sci. Med.* 63:946–56
64. Giles-Corti B, Foster S, Shilton T, Falconer R. 2010. The co-benefits for health of investing in active transportation. *NSW Public Health Bull.* 21:122–27
65. Global Energy Assess. (GEA) Writing Team. 2012. *Global Energy Assessment: Toward a Sustainable Future*, ed. TB Johansson, N Nakicenovic, A Patwardhan, L Gomez-Echeverri. Cambridge, UK/New York: Cambridge Univ. Press/Laxenburg, Austria: Int. Inst. Appl. Syst. Anal.
66. Gohlke JM, Thomas R, Woodward A, Campbell-Lendrum D, Prüss-Üstün A, et al. 2011. Estimating the global public health implications of electricity and coal consumption. *Environ. Health Perspect.* 119:821–26
67. Goldemberg J, ed. 2000. *World Energy Assessment: Energy and the Challenge of Sustainability*. New York: UNDP/UNDESA/World Energy Counc.
68. Gomes Ade C, de Paula MB, Duarte AMR, Lima MA, Malafronte RS, et al. 2008. Epidemiological and ecological aspects related to malaria in the area of influence of the lake at Porto Primavera dam, in western São Paulo State, Brazil. *Rev. Inst. Med. Trop. São Paulo* 50:2887–95
69. Graf WL. 1999. Dam nation: a geographic census of American dams and their large-scale hydrologic impacts. *Water Resour. Res.* 35:1305–11
70. Grattan LM, Roberts S, Mahan WT Jr, McLaughlin PK, Otwell WS, Morris JG Jr. 2011. The early psychological impacts of the Deepwater Horizon oil spill on Florida and Alabama communities. *Environ. Health Perspect.* 119:838–43
71. Grosche B, Kreuzer M, Kreisheimer M, Schnelzer M, Tschense A. 2006. Lung cancer risk among German male uranium miners: a cohort study, 1946–1998. *Br. J. Cancer* 95:1280–87
72. Grubler A, Johansson TB, Mundaca L, Nakicenovic N, Pachauri S, et al. 2012. Energy primer. See Ref. 65, pp. 99–150
73. Haddon W Jr. 1980. Advances in the epidemiology of injuries as a basis for public health policy. *Public Health Rep.* 95:411–21
74. Haines A. 2007. Energy and health series. *Lancet* 370:922
75. Haines A, McMichael AJ, Smith KR, Roberts I, Woodcock J, et al. 2009. Public health benefits of strategies to reduce greenhouse-gas emissions: overview and implications for policy makers. *Lancet* 374:2104–14
76. Haines A, Smith KR, Anderson D, Epstein PR, McMichael AJ, et al. 2007. Policies for accelerating access to clean energy, improving health, advancing development, and mitigating climate change. *Lancet* 370:1264–81

76a. Hall C, Tharakan P, Hallock J, Cleveland C, Jefferson M. 2003. Hydrocarbons and the evolution of human culture. *Nature* 426:318–22

77. Hanna R, Duflo E, Greenstone M. 2012. *Up in smoke: the influence of household behavior on the long-run impact of improved cooking stoves.* Tech. Rep. Work. Pap. No. 12-10, MIT Dep. Econ.
78. Hanning CD, Evans A. 2012. Wind turbine noise. *BMJ* 344:e1527
79. Harrison JP. 2011. Wind turbine noise. *Bull. Sci. Technol. Soc.* 31:256–61
80. Hatheway AW. 2012. *Remediation of Former Manufactured Gas Plants and Other Coal-Tar Sites*. Boca Raton, FL: CRC Press
81. He G, Ying B, Liu J, Gao S, Shen S, et al. 2005. Patterns of household concentrations of multiple indoor air pollutants in China. *Environ. Sci. Technol.* 39:991–98
82. Health Effects Inst. 2010. *Outdoor Air Pollution and Health in the Developing Countries of Asia: A Comprehensive Review*. Spec. Rep. 18. Boston: Health Effects Inst.
83. Hendryx M, Ahern MM. 2008. Relations between health indicators and residential proximity to coal mining in West Virginia. *Am. J. Public Health* 98:669–71
84. Hill J, Nelson E, Tilman D, Polasky S, Tiffany D. 2006. Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. *Proc. Natl. Acad. Sci. USA* 103:11206–10
85. Hill J, Polasky S, Nelson E, Tilman D, Huo H, et al. 2009. Climate change and health costs of air emissions from biofuels and gasoline. *Proc. Natl. Acad. Sci. USA* 106:2077–82
86. Holt E. 2010. Debate over health effects of Chernobyl is re-ignited. *Lancet* 375:1424–25
87. Holtzman DC. 2011. Mountaintop removal mining: digging into community health concerns. *Environ. Health Perspect.* 119:A476–83. Erratum. 2011. *Environ. Health Perspect.* 119(12):A509
88. Hosgood H III, Wei H, Sapkota A, Choudhury I, Bruce N, et al. 2011. Household coal use and lung cancer: systematic review and meta-analysis of case-control studies, with an emphasis on geographic variation. *Int. J. Epidemiol.* 40:719–28
89. Hosier RH. 2004. Energy ladder in developing countries. *Encycl. Energy* 2:423–35
90. Howarth RW, Bringezu S, Martinelli LA, Santoro R, Messem D, Sala OE. 2009. Introduction: Biofuels and the environment in the 21st century. In *Biofuels: Environmental Consequences and Interactions with Changing Land Use. Proc. SCOPE Int. Biofuels Proj. Rapid Assess., 22–25 Sept. 2008, Gummersbach, Ger.*, ed. RW Howarth, S Bringezu, pp. 15–36. Ithaca, NY: Cornell Univ.
91. Howarth RW, Santoro R, Ingraffea A. 2011. Methane and the greenhouse-gas footprint of natural gas from shale formations. *Clim. Change* 106:679–90
92. Howden-Chapman P, Viggers H, Chapman R, O'Sullivan K, Barnard L, Lloyd B. 2011. Tackling cold housing and fuel poverty in New Zealand: a review of policies, research, and health impacts. *Energy Policy* 49:134–42
93. Hvistendahl M. 2007. Coal ash is more radioactive than nuclear waste. *Sci. Am.* Dec. 13. **http://www.scientificamerican.com/article.cfm?id=coal-ash-is-more-radioactive-than-nuclear-waste**
94. Hwang S, Cao Y, Xi J. 2011. The short-term impact of involuntary migration in China's Three Gorges: a prospective study. *Soc. Indic. Res.* 101:73–92
95. Hwang S, Xi J, Cao Y, Feng X, Qiao X. 2007. Anticipation of migration and psychological stress and the Three Gorges Dam project, China. *Soc. Sci. Med.* 65:1012–24
96. Insur. Inst. Highw. Saf. (IIHS). 2009. Car size and weight are crucial. *IIHS Status Rep.* 44:1–8
97. Int. Agency Res. Cancer (IARC). 2010. Household use of solid fuels. In *IARC Monogr. Eval. Carcinog. Risks Hum.*, Vol. 95: *Household Use of Solid Fuels and High-Temperature Frying*, pp. 43–307. Lyon, Fr: World Health Organ. (WHO), IARC. **http://monographs.iarc.fr/ENG/Monographs/vol95/mono95.pdf**
98. Int. At. Energy Agency. 2002. *Follow-Up of Delayed Health Consequences of Acute Accidental Radiation Exposure. Lessons to Be Learned from Their Medical Management.* IAEA-TECDOC-1300. Vienna: IAEA. **http://www-pub.iaea.org/mtcd/publications/pdf/te_1300_web.pdf**
99. Int. Comm. on Large Dams (ICOLD). *World Register of Dams*. Paris: ICOLD. **http://www.icold-cigb.net/GB/World_register/world_register.asp**
100. Intergov. Panel on Clim. Change (IPCC). 2007. *Climate Change 2007: Impacts, Adaptation and Vulnerability*, ed. ML Parry, OF Canziani, JP Palutikof, PJ van der Linden, CE Hanson. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK: Cambridge Univ. Press. **http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_wg2_report_impacts_adaptation_and_vulnerability.htm**

101. Ito K, De Leon S, Lippmann M. 2005. Associations between ozone and daily mortality: analysis and meta-analysis. *Epidemiology* 16:446–57

102. Janssen S, Vos H, Eisses A, Pedersen E. 2011. A comparison between exposure-response relationships for wind turbine annoyance and annoyance due to other noise sources. *J. Acoust. Soc. Am.* 130:3746–53

103. Jarrett J, Woodcock J, Griffiths U, Chalabi Z, Edwards P, et al. 2012. Effect of increasing active travel in urban England and Wales on costs to the National Health Service. *Lancet* 379:2198–205

104. Jennings NS. 1998. Mining: an overview. See Ref. 208, 3:74.72–74

105. Jerrett M, Burnett RT, Pope CA 3rd, Ito K, Thurston G, et al. 2009. Long-term ozone exposure and mortality. *N. Engl. J. Med.* 360:1085–95

106. Jetter J, Zhao Y, Smith KR, Khan B, Yelverton T, et al. 2012. Pollutant emissions and energy efficiency under controlled conditions for household biomass cookstoves and implications for metrics useful in setting International Test Standards. *Environ. Sci. Technol.* 46:10827–34

107. Ji M, Cohan DS, Bell ML. 2011. Meta-analysis of the association between short-term exposure to ambient ozone and respiratory hospital admissions. *Environ. Res. Lett.* 6:21779304

108. Jobin W. 1999. *Dams and Disease: Ecological Design and Health Impacts of Large Dams, Canals and Irrigation Systems*. London: Spon

109. Kaatsch P, Spix C, Schulze-Rath R, Schmiedel S, Blettner M. 2008. Leukaemia in young children living in the vicinity of German nuclear power plants. *Int. J. Cancer* 122:721–26

110. Keiser J, Utzinger J, De Castro MC, Smith TA, Tanner M, Singer BH. 2004. Urbanization in sub-Saharan Africa and implication for malaria control. *Am. J. Trop. Med. Hyg.* 71:118–27

111. Kibert CJ. 2007. *Sustainable Construction: Green Building Design and Delivery*. Hoboken, NJ: Wiley

112. Kibret S, McCartney M, Lautze J, Jayasinghe G. 2009. *Malaria Transmission in the Vicinity of Impounded Water: Evidence from the Koka Reservoir, Ethiopia. I.* IWMI Res. Rep. 132. Colombo: Int. Water Manag. Inst. (IWMI). **http://www.iwmi.cgiar.org/Publications/IWMI_Research_Reports/PDF/PUB132/RR132.pdf**

113. Kim CS, Alexis NE, Rappold AG, Kehrl H, Hazucha MJ, et al. 2011. Lung function and inflammatory responses in healthy young adults exposed to 0.06 ppm ozone for 6.6 hours. *Am. J. Respir. Crit. Care Med.* 183:1215–21

114. Kirkeleit J, Riise T, Bjørge T, Moen B, Bråtveit M, Christiani D. 2010. Increased risk of oesophageal adenocarcinoma among upstream petroleum workers. *Occup. Environ. Med.* 67:335–40

115. Knopper L, Ollson C. 2011. Health effects and wind turbines: a review of the literature. *Environ. Health* 10:78–87

116. Kosnik L. 2008. The potential of water power in the fight against global warming in the U.S. *Energy Policy* 36:3252–65

117. Kraus RS. 1998. Oil exploration and drilling. See Ref. 208, 3:75.1–14

118. Künzli N, Jerrett M, Garcia-Esteban R, Basagaña X, Beckermann B, et al. 2010. Ambient air pollution and the progression of atherosclerosis in adults. *PLoS One* 5:e9096

119. Künzli N, Kaiser R, Medina S, Studnicka M, Chanel O, et al. 2000. Public-health impact of outdoor and traffic-related air pollution: a European assessment. *Lancet* 356:795–801

120. Lam NL, Smith KR, Gauthier A, Bates MN. 2012. Kerosene: a review of household uses and their hazards in low- and middle-income countries. *J. Toxicol. Environ. Health B* 15:396–432

121. Lapola DM, Schaldach R, Alcamo J, Bondeau A, Koch J, et al. 2010. Indirect land-use changes can overcome carbon savings from biofuels in Brazil. *Proc. Natl. Acad. Sci. USA* 107:3388–93

122. Lautze J, McCartney M, Kirshen P, Olana D, Jayasinghe G, Spielman A. 2007. Effect of a large dam on malaria risk: the Koka reservoir in Ethiopia. *Trop. Med. Int. Health* 12:982–89

123. Leung CC, Yu IT, Chen W. 2012. Silicosis. *Lancet* 379:2008–18

124. Levy J, Baxter L, Schwartz J. 2009. Uncertainty and variability in health-related damages from coal-fired power plants in the United States. *Risk Anal.* 29:1000–14

125. Li YS, Raso G, Zhao ZY, He Y, Ellis MK, McManus DP. 2007. Large water management projects and schistosomiasis control, Dongting Lake region, China. *Emerg. Infect. Dis.* 13:973–79

126. Lim SS, Vos T, Flaxman AD, Danaei G, Shibuya K, et al. 2012. A comparative risk assessment of burden of disease and injury attributable to 67 risk factor clusters in 21 regions, 1990–2010: a systematic analysis for the Global Burden of Disease Study 2010. *Lancet.* 380:2224–60

127. Lima I, Ramos F, Bambace L, Rosa R. 2008. Methane emissions from large dams as renewable energy resources: a developing nation perspective. *Mitig. Adapt. Strateg. Glob. Change* 13:193–206

128. Lindsay G, Macmillan A, Woodward A. 2011. Moving urban trips from cars to bicycles: impact on health and emissions. *Aust. N. Z. J. Public Health* 35:54–60

129. Liu JF, Mauzerall DL, Horowitz LW. 2009. Evaluating inter-continental transport of fine aerosols: (2) Global health impact. *Atmos. Environ.* 43:4339–47

130. Loganovsky K, Havenaar JM, Tintle NL, Guey LT, Kotov R, Bromet E. 2008. The mental health of clean-up workers 18 years after the Chernobyl accident. *Psychol. Med.* 38:481–88

131. Mäkinen K, Khan S. 2010. Policy considerations for greenhouse gas emissions from freshwater reservoirs. *Water Altern.* 3:91–105

132. Markandya A, Armstrong BG, Hales S, Chiabai A, Criqui P, et al. 2009. Public health benefits of strategies to reduce greenhouse-gas emissions: low-carbon electricity generation. *Lancet* 374:2006–15

133. Masera OR, Saatkamp BD, Kammen DM. 2000. From linear fuel switching to multiple cooking strategies: a critique and alternative to the energy ladder model. *World Dev.* 28:2083–103

134. McCormick R. 2007. The impact of biodiesel on pollutant emissions and public health. *Inhal. Toxicol.* 19:1033–39

135. McCracken JP, Schwartz J, Bruce N, Mittleman M, Ryan LM, Smith KR. 2009. Combining individual- and group-level exposure information: child carbon monoxide in the Guatemala Woodstove Randomized Control Trial. *Epidemiology* 20:127–36

136. McDonald-Wilmsen B, Webber M. 2010. Dams and displacement: raising the standards and broadening the research agenda. *Water Altern.* 3:142–61

137. McMichael AJ. 2012. Insights from past millennia into climatic impacts on human health and survival. *Proc. Natl. Acad. Sci. USA* 109:4730–37

138. Mitka M. 2012. Rigorous evidence slim for determining health risks from natural gas fracking. *JAMA* 307:2135–36

139. Morris R, Pollack A, Mansell G, Lindhjem C, Jia Y, Wilson G. 2003. *Impact of Biodiesel Fuels on Air Quality and Human Health*. Golden, CO: Natl. Renew. Energy Lab.

140. Moysich K, McCarthy P, Hall P. 2011. 25 years after Chernobyl: lessons for Japan? *Lancet Oncol.* 12:416–18

141. Mueller S, Anderson J, Wallington T. 2011. Impact of biofuel production and other supply and demand factors on food price increases in 2008. *Biomass Bioenergy* 36:1623–32

142. Naeher LP, Brauer M, Lipsett M, Zelikoff JT, Simpson CD, et al. 2007. Woodsmoke health effects: a review. *Inhal. Toxicol.* 19:67–106

143. Natl. Res. Counc. 1999. *Health Effects of Exposure to Radon: BEIR VI.* Washington, DC: Natl. Acad. Press

144. Natl. Res. Counc. 2002. *Coal Waste Impoundments: Risks, Responses, and Alternatives.* Washington, DC: Natl. Acad. Press

145. Natl. Res. Counc. 2006. *Health Risks from Exposure to Low Levels of Ionizing Radiation: BEIR VII Phase 2.* Washington, DC: Natl. Acad. Press

146. Natl. Res. Counc. 2006. *Managing Coal Combustion Residues in Mines.* Washington, DC: Natl. Acad. Press

147. Natl. Res. Counc. 2008. *Estimating Mortality Risk Reduction and Economic Benefits from Controlling Ozone Air Pollution.* Washington, DC: Natl. Acad. Press

148. Natl. Res. Counc. 2010. *The Hidden Cost of Energy: Unpriced Consequences of Energy Production and Use.* Washington, DC: Natl. Acad. Press. 506 pp.

149. Nussbaum R. 2007. The Chernobyl nuclear catastrophe: unacknowledged health detriment. *Environ. Health Perspect.* 115:A238–39

150. Olmstead J. 2009. *Fueling Resistance? Antibiotics in Ethanol Production*. Minneapolis: Inst. Agric. Trade Policy.

151. O'Neill BC, Liddle B, Jiang L, Smith KR, Pachauri S, et al. 2012. Demographic change and CO2 emissions. *Lancet* 380:157–64

152. Onuoha F. 2008. Oil pipeline sabotage in Nigeria: dimensions, actors and implications for national security. *Afr. Secur. Rev.* 17:99–115

153. Osborn S, Vengosh A, Warner N, Jackson R. 2011. Methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing. *Proc. Natl. Acad. Sci. USA* 108:8172–76

154. Pachauri S. 2011. Reaching an international consensus on defining modern energy access. *Energy Syst.* 3:235–40
155. Pachauri S, Brew-Hammond A, Barnes DF, Bouille DH, Gitonga S, et al. 2012. Energy access for development. See Ref. 65, pp. 1401–58
156. Pacyna EG, Pacyna JM, Sundseth K, Munthe J, Kindbom K, et al. 2010. Global emission of mercury to the atmosphere from anthropogenic sources in 2005 and projections to 2020. *Atmos. Environ.* 44:2487–99
157. Palinkas L, Petterson J, Russell J, Downs M. 1993. Community patterns of psychiatric disorders after the Exxon Valdez oil spill. *Am. J. Psychiatry* 150:1517–23
158. Palmer MA, Bernhardt ES, Schlesinger WH, Eshleman KN, Foufoula-Georgiou E, et al. 2010. Science and regulation. Mountaintop mining consequences. *Science* 327:148–49
159. Pedersen E, Persson WK. 2007. Wind turbine noise, annoyance and self-reported health and well-being in different living environments. *Occup. Environ. Med.* 64:480–86
160. Pedersen E, van den Berg F, Bakker R, Bouma J. 2009. Response to noise from modern wind farms in The Netherlands. *J. Acoust. Soc. Am.* 126:634–43
161. Peltier RE, Hsu S-I, Lall R, Lippmann M. 2009. Residual oil combustion: a major source of airborne nickel in New York City. *J. Expo. Sci. Environ. Epidemiol.* 19:603–13
162. Peltier RE, Lippmann M. 2010. Residual oil combustion: 2. Distributions of airborne nickel and vanadium within New York City. *J. Expo. Sci. Environ. Epidemiol.* 20:342–50
163. Petryna A. 2002. *Life Exposed: Biological Citizens after Chernobyl*. Princeton, NJ: Princeton Univ. Press
164. Pirrone N, Cinnirella S, Feng X, Finkelman R, Friedli H, et al. 2010. Global mercury emissions to the atmosphere from anthropogenic and natural sources. *Atmos. Chem. Phys.* 10:5951–64
165. Pope CA 3rd, Burnett RT, Turner MC, Cohen A, Krewski D, et al. 2011. Lung cancer and cardiovascular disease mortality associated with ambient air pollution and cigarette smoke: shape of the exposure-response relationships. *Environ. Health Perspect.* 119:1616–21
166. Pope CA 3rd, Burnett RT, Thun MJ, Calle EE, Krewski D, et al. 2002. Lung cancer, cardiopulmonary mortality and long-term exposure to fine particulate air pollution. *JAMA* 287:1132–41
167. Pope CA 3rd, Ezzati M, Dockery D. 2009. Fine-particulate air pollution and life expectancy in the United States. *N. Engl. J. Med.* 360:376–86
168. Pope DP, Mishra V, Thompson L, Siddiqui AR, Rehfuess EA, et al. 2010. Risk of low birth weight and stillbirth associated with indoor air pollution from solid fuel use in developing countries. *Epidemiol. Rev.* 32:70–81
169. Poschen P. 1998. Forestry. See Ref. 208, 3:68.2–68.6
170. PT Pertamina (Persero), World LP Gas Assoc. 2012. *Kerosene to LP Gas Conversion Programme in Indonesia: A Case Study of Domestic Energy*. Neuilly-sur-Seine, Fr.: World LP Gas Assoc./Central Jakarta, Indones.: Pertamina
171. Rahu K, Rahu M, Tekkel M, Bromet E. 2006. Suicide risk among Chernobyl cleanup workers in Estonia still increased: an updated cohort study. *Ann. Epidemiol.* 16:917–19
172. Rallo M, Lopez-Anton M, Contreras M, Maroto-Valer M. 2012. Mercury policy and regulations for coal-fired power plants. *Environ. Sci. Pollut. Res. Int.* 19:1084–96
173. Raymond-Whish S, Mayer LP, O'Neal T, Martinez A, Sellers MA, et al. 2007. Drinking water with uranium below the U.S. EPA water standard causes estrogen receptor-dependent responses in female mice. *Environ. Health Perspect.* 115:1711–16
174. REN21 (Renewable Energy Policy Network for the 21st Century). 2012. *Renewables 2012 Global Status Report*. Paris: REN21 Secr.
175. Riahi K, Dentener F, Gielen D, Grubler A, Jewell J, et al. 2012. Energy pathways for sustainable development. See Ref. 65, pp. 1203–306
176. Ridley CE, Clark CM, Leduc SD, Bierwagen BG, Lin BB, et al. 2012. Biofuels: network analysis of the literature reveals key environmental and economic unknowns. *Environ. Sci. Technol.* 46:1309–15
177. Rissel CE. 2009. Active travel: a climate change mitigation strategy with co-benefits for health. *NSW Public Health Bull.* 20:10–13
178. Robertson GP, Dale VH, Doering OC, Hamburg SP, Melillo JM, et al. 2008. Agriculture: sustainable biofuels redux. *Science* 322:49–50

179. Ross JK. 2009. Offshore industry shift work—health and social considerations. *Occup. Med.* 59:310–15
180. Ross MH, Murray J. 2004. Occupational respiratory disease in mining. *Occup. Med.* 54:304–10
181. Ruiz-Mercado I, Canuz E, Smith K. 2012. Temperature dataloggers as stove use monitors (SUMs): field methods and signal analysis. *Biomass Bioenergy* 47:459–68
182. Runge C, Senauer B. 2007. How biofuels could starve the poor. *Foreign Aff.* 86:41–53
183. Saenko V, Ivanov V, Tsyb A, Bogdanova T, Tronko M, et al. 2011. The Chernobyl accident and its consequences. *Clin. Oncol.* 23:234–43
184. Schlünssen V, Madsen AM, Skov S, Sigsgaard T. 2011. Does the use of biofuels affect respiratory health among male Danish energy plant workers? *Occup. Environ. Med.* 68:467–73
185. Schwartz B, Parker C, Hess J, Frumkin H. 2011. Public health and medicine in an age of energy scarcity: the case of petroleum. *Am. J. Public Health* 101:1560–67
186. Schwartz J, Coull B, Laden F, Ryan L. 2008. The effect of dose and timing of dose on the association between airborne particles and survival. *Environ. Health Perspect.* 116:64–69
187. Searchinger T, Heimlich R, Houghton RA, Dong F, Elobeid A, et al. 2008. Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science* 319:1238–40
188. Seto EY, Wu W, Liu HY, Chen HG, Hubbard A, et al. 2008. Impact of changing water levels and weather on *Oncomelania hupensis hupensis* populations, the snail host of *Schistosoma japonicum*, downstream of the Three Gorges Dam. *EcoHealth* 5:149–58
189. Sheehan J. 2009. Biofuels and the conundrum of sustainability. *Curr. Opin. Biotechnol.* 20:318–24
190. Shepherd D, McBride D, Welch D, Dirks K, Hill E. 2011. Evaluating the impact of wind turbine noise on health-related quality of life. *Noise Health* 13:333–39
191. Silicon Valley Toxics Coalit. 2009. *Toward a Just and Sustainable Solar Energy Industry*. San Francisco: Silicon Valley Toxics Coalit.
192. Sinton JE, Smith KR, Peabody JW, Yaping L, Xiliang Z, et al. 2004. An assessment of programs to promote improved household stoves in China. *Energy Sustain. Dev.* 8:33–52
193. Smil V. 2005. *Energy at the Crossroads: Global Perspectives and Uncertainties*. Cambridge, MA: MIT Press
194. Smith KR, McCracken JM, Weber MW, Hubbard H, Jenny A, et al. 2011. RESPIRE: a randomised controlled trial of the impact of reducing household air pollution on childhood pneumonia in Guatemala. *Lancet* 378:1717–26
195. Smith KR, Balakrishnan K. 2009. Mitigating climate, meeting the MDGs, and blunting chronic disease: the health co-benefits landscape. In *Commonwealth Health Ministers' Update 2009*, pp. 59–65. London: Commonwealth Secr. **http://www.thecommonwealth.org/files/190381/FileName/4-KirkSmith_2009.pdf**
196. Smith KR, Balakrishnan K, Butler C, Chafe Z, Fairlie I, et al. 2012. Energy and health. See Ref. 65, pp. 255–324
197. Smith KR, Dutta K. 2011. Cooking with gas. *Energy Sustain. Dev.* 15:115–16
198. Smith KR, Ezzati M. 2005. How environmental health risks change with development: the epidemiologic and environmental risk transitions revisited. *Annu. Rev. Environ. Resour.* 30:291–333
199. Smith KR, Haigler E. 2008. Co-benefits of climate mitigation and health protection in energy systems: scoping methods. *Annu. Rev. Public Health* 29:11–25
200. Smith KR, Jerrett M, Anderson HR, Burnett RT, Stone V, et al. 2009. Public health benefits of strategies to reduce greenhouse-gas emissions: health implications of short-lived greenhouse pollutants. *Lancet* 374:2091–103
201. Smith KR, McCracken JP, Thompson L, Edwards R, Shields KN, et al. 2010. Personal child and mother carbon monoxide exposures and kitchen levels: methods and results from a randomized trial of woodfired chimney cookstoves in Guatemala (RESPIRE). *J. Expo. Sci. Environ. Epidemiol.* 20:406–16
202. Smith KR, Peel J. 2010. Mind the gap. *Environ. Health Perspect.* 118:1643–45
203. Smith KR, Pillarisetti A. 2012. A short history of woodsmoke and implications for Chile. *Estud. Públicos* 126:163–79
204. Solomon GM, Janssen S. 2010. Health effects of the Gulf oil spill. *JAMA* 304:1118–19
205. Sorahan T. 2007. Mortality of UK oil refinery and petroleum distribution workers, 1951–2003. *Occup. Med.* 57:177–85

206. Spix C, Schmiedel S, Kaatsch P, Schulze-Rath R, Blettner M. 2008. Case-control study on childhood cancer in the vicinity of nuclear power plants in Germany 1980–2003. *Eur. J. Cancer* 44:275–84

207. Steinmann P, Keiser J, Bos R, Tanner M, Utzinger J. 2006. Schistosomiasis and water resources development: systematic review, meta-analysis, and estimates of people at risk. *Lancet Infect. Dis.* 6:411–25

208. Stellman JM, ed. 1998. *Encyclopaedia of Occupational Health and Safety*. Geneva: Int. Labour Organ. 4th ed.

209. Tanigawa K, Hosoi Y, Hirohashi N, Iwasaki Y, Kamiya K. 2012. Loss of life after evacuation: lessons learned from the Fukushima accident. *Lancet* 379:889–91

210. Taylor D. 2010. On the job with solar PV. *Environ. Health Perspect.* 118:A19

211. Tolunay E, Chockalingam A, eds. 2012. *Indoor and Outdoor Air Pollution, and Cardiovascular Health. Global Heart* (Spec. Issue) 7(3):197–274

212. Toman M, Jemelkova B. 2003. Energy and economic development: an assessment of the state of knowledge. *Energy J.* 24:93–112

213. Tsai S, Wendt J, Cardarelli K, Fraser A. 2003. A mortality and morbidity study of refinery and petrochemical employees in Louisiana. *Occup. Environ. Med.* 60:627–33

214. Turkenburg WC, Arent DJ, Bertani R, Faaij A, Hand M, et al. 2012. Renewable energy. See Ref. 65, pp. 761–900

215. UN Dev. Progr. 2009. *The Energy Access Situation in Developing Countries: A Review Focused on Least Developed Countries and Sub-Saharan Africa*. Nairobi, Kenya: UN

216. UN Inst. Disarm. Res. 2008. The health hazards of depleted uranium. In *Disarmament Forum*, ed. I Fairlie, 3:3–16. Geneva: UNIDIR

217. UN Sci. Comm. Eff. At. Radiat. 2000. Annex J: Exposures and effects of the Chernobyl accident. In *Sources and Effects of Ionising Radiation. UNSCEAR 2000 Report to the General Assembly with Scientific Annexes. Volume II: Effects*, pp. 451–566. New York: UN

218. UN Sci. Comm. Eff. At. Radiat. 2012. *Background Information for Journalists. UNSCEAR Assessment of the Fukushima-Daiichi Accident*. Vienna: UN. **http://www.unis.unvienna.org/pdf/2012/UNSCEAR_Backgrounder.pdf**

219. Vennemo H, Aunan K, Jinghua F, Holtedahl P, Tao H, Seip H. 2006. Domestic environmental benefits of China's energy-related CDM potential. *Clim. Change* 75:215–39

220. von Hippel F, Bunn M, Diakov A, Ding M, Goldston R, et al. 2012. Nuclear energy. See Ref. 65, pp. 1069–130

221. Wakeford R. 2009. Radiation in the workplace—a review of studies of the risks of occupational exposure to ionising radiation. *J. Radiol. Prot.* 29:A61–79

222. Walsh MP. 2008. Ancillary benefits for climate change mitigation and air pollution control in the world's motor vehicle fleets. *Annu. Rev. Public Health* 29:1–9

223. Weinhold B. 2011. Alberta's oil sands: hard evidence, missing data, new promises. *Environ. Health Perspect.* 119:A126–31

224. Weinmayr G, Romeo E, De Sario M, Weiland S, Forastiere F. 2010. Short-term effects of PM10 and NO2 on respiratory health among children with asthma or asthma-like symptoms: a systematic review and meta-analysis. *Environ. Health Perspect.* 118:449–57

225. Wilkinson P, Smith KR, Davies M, Adair H, Armstrong BG, et al. 2009. Public health benefits of strategies to reduce greenhouse-gas emissions: household energy. *Lancet* 374:1917–29

226. Wilkinson P, Smith KR, Joffe M, Haines A. 2007. A global perspective on energy: health effects and injustices. *Lancet* 370:965–78

227. Woodcock J, Banister D, Edwards P, Prentice AM, Roberts I. 2007. Energy and transport. *Lancet* 370:1078–88

228. Woodcock J, Edwards P, Tonne C, Armstrong BG, Ashiru O, et al. 2009. Public health benefits of strategies to reduce greenhouse-gas emissions: urban land transport. *Lancet* 374:1930–43

229. World Bank. 2004. *Involuntary Resettlement Sourcebook: Planning and Implementation in Development Projects*. Washington, DC: World Bank. **http://www4.worldbank.org/afr/ssatp/Resources/HTML/Gender-RG/Source%20%20documents%5CTool%20Kits%20&%20Guides%5CDesigning%20Projects/TLPRO10%20invol%20resettlementsourcebookWB.pdf**

230. World Comm. Dams. 2000. *Dams and Development: A New Framework for Decision-Making*. London: Earthscan. **http://www.internationalrivers.org/files/attached-files/world_commission_on_dams_final_report.pdf**

231. World Health Organ. (WHO). 2006. *Air Quality Guidelines: Global Update for 2005*. Copenhagen: WHO, Reg. Off. Eur. **http://www.who.int/phe/health_topics/outdoorair_aqg/en/**

232. Wrangham R. 2010. *Catching Fire: How Cooking Made Us Human*. New York: Basic Books

233. Xi J, Hwang S. 2011. Relocation stress, coping, and sense of control among resettlers resulting from China's Three Gorges Dam Project. *Soc. Indic. Res.* 104:507–22

234. Yewhalaw D, Legesse W, Van Bortel W, Gebre-Selassie S, Kloos H, et al. 2009. Malaria and water resource development: the case of Gilgel-Gibe hydroelectric dam in Ethiopia. *Malar. J.* 8:21

235. Younger M, Morrow-Almeida H, Vindigni SM, Dannenberg AL. 2008. The built environment, climate change, and health: opportunities for co-benefits. *Am. J. Prev. Med.* 35:517–26

236. Zhou Y, Luckow P, Smith SJ, Clarke L. 2012. Evaluation of global onshore wind energy potential and generation costs. *Environ. Sci. Technol.* 46:7857–64

237. Zhu HM, Xiang S, Wu XH, Zhou XN. 2008. Three Gorges Dam and its impact on the potential transmission of schistosomiasis in regions along the Yangtze River. *EcoHealth* 5:137–48

Annual Review of Public Health
Volume 34, 2013

Contents

Symposium: Developmental Origins of Adult Disease

Epidemiology and Biostatistics

Environmental and Occupational Health

Public Health Practice

Social Environment and Behavior

Health Services

Indexes

Errata

An online log of corrections to *Annual Review of Public Health* articles may be found at http://publhealth.annualreviews.org/

Annu. Rev. Public. Health. 2013.34:159-188. Downloaded from www.annualreviews.org
by Portland State University on 05/14/14. For personal use only.

ANNUAL REVIEWS

It's about time. Your time. It's time well spent.

New From Annual Reviews:

Annual Review of Statistics and Its Application

Volume 1 • Online January 2014 • http://statistics.annualreviews.org

Editor: **Stephen E. Fienberg,** *Carnegie Mellon University*

Associate Editors: **Nancy Reid,** *University of Toronto*
Stephen M. Stigler, *University of Chicago*

The *Annual Review of Statistics and Its Application* aims to inform statisticians and quantitative methodologists, as well as all scientists and users of statistics about major methodological advances and the computational tools that allow for their implementation. It will include developments in the field of statistics, including theoretical statistical underpinnings of new methodology, as well as developments in specific application domains such as biostatistics and bioinformatics, economics, machine learning, psychology, sociology, and aspects of the physical sciences.

Complimentary online access to the first volume will be available until January 2015.

TABLE OF CONTENTS:

- *What Is Statistics?* Stephen E. Fienberg
- *A Systematic Statistical Approach to Evaluating Evidence from Observational Studies,* David Madigan, Paul E. Stang, Jesse A. Berlin, Martijn Schuemie, J. Marc Overhage, Marc A. Suchard, Bill Dumouchel, Abraham G. Hartzema, Patrick B. Ryan
- *The Role of Statistics in the Discovery of a Higgs Boson,* David A. van Dyk
- *Brain Imaging Analysis,* F. DuBois Bowman
- *Statistics and Climate,* Peter Guttorp
- *Climate Simulators and Climate Projections,* Jonathan Rougier, Michael Goldstein
- *Probabilistic Forecasting,* Tilmann Gneiting, Matthias Katzfuss
- *Bayesian Computational Tools,* Christian P. Robert
- *Bayesian Computation Via Markov Chain Monte Carlo,* Radu V. Craiu, Jeffrey S. Rosenthal
- *Build, Compute, Critique, Repeat: Data Analysis with Latent Variable Models,* David M. Blei
- *Structured Regularizers for High-Dimensional Problems: Statistical and Computational Issues,* Martin J. Wainwright
- *High-Dimensional Statistics with a View Toward Applications in Biology,* Peter Bühlmann, Markus Kalisch, Lukas Meier
- *Next-Generation Statistical Genetics: Modeling, Penalization, and Optimization in High-Dimensional Data,* Kenneth Lange, Jeanette C. Papp, Janet S. Sinsheimer, Eric M. Sobel
- *Breaking Bad: Two Decades of Life-Course Data Analysis in Criminology, Developmental Psychology, and Beyond,* Elena A. Erosheva, Ross L. Matsueda, Donatello Telesca
- *Event History Analysis,* Niels Keiding
- *Statistical Evaluation of Forensic DNA Profile Evidence,* Christopher D. Steele, David J. Balding
- *Using League Table Rankings in Public Policy Formation: Statistical Issues,* Harvey Goldstein
- *Statistical Ecology,* Ruth King
- *Estimating the Number of Species in Microbial Diversity Studies,* John Bunge, Amy Willis, Fiona Walsh
- *Dynamic Treatment Regimes,* Bibhas Chakraborty, Susan A. Murphy
- *Statistics and Related Topics in Single-Molecule Biophysics,* Hong Qian, S.C. Kou
- *Statistics and Quantitative Risk Management for Banking and Insurance,* Paul Embrechts, Marius Hofert

Access this and all other Annual Reviews journals via your institution at www.annualreviews.org.

ANNUAL REVIEWS | Connect With Our Experts

Tel: 800.523.8635 (US/CAN) | Tel: 650.493.4400 | Fax: 650.424.0910 | Email: service@annualreviews.org