

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 Schneider¹²

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

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

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

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

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

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

⁸Center 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: kjellstrom@yahoo.com

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

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

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

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

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

First published online as a Review in Advance on
January 16, 2013

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

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

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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.

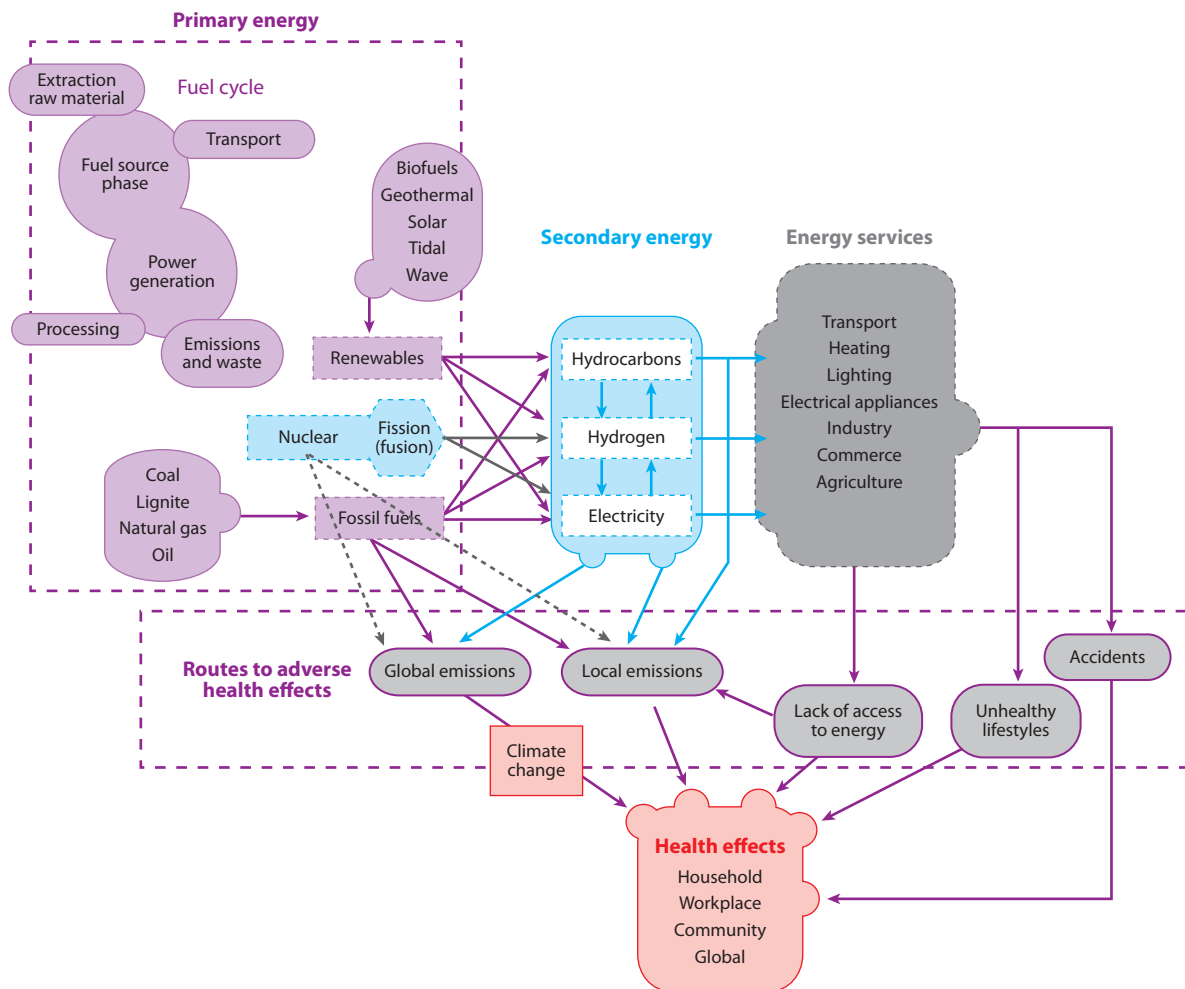


Figure 1

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

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

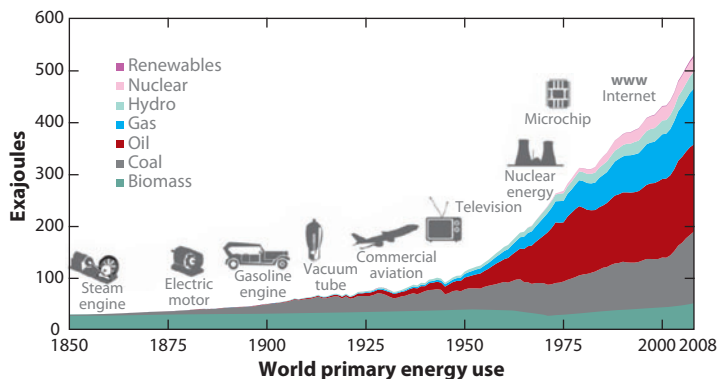


Figure 2

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 \sim 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 (CO₂) and other climate-altering pollutants from energy systems.

HOUSEHOLD ENERGY

Patterns of Household Fuel Use

The *Global Energy Assessment* estimates that in 2005 \sim 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).

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 $7,800 \pm 11,200 \mu\text{g}/\text{m}^3$), followed by charcoal (mean $3,900 \pm 8,400 \mu\text{g}/\text{m}^3$) and wood (mean $2,100 \pm 3,900 \mu\text{g}/\text{m}^3$). 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).

HAP: household air pollution

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

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 Acetaldehyde Phenols Pyrene, Benzopyrene Benzo(a)pyrene Dibenzopyrenes Dibenzocarbazoles Cresols	Carcinogenicity Co-carcinogenicity Mucus coagulation, cilia toxicity Increased allergic sensitization Increased airway reactivity

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

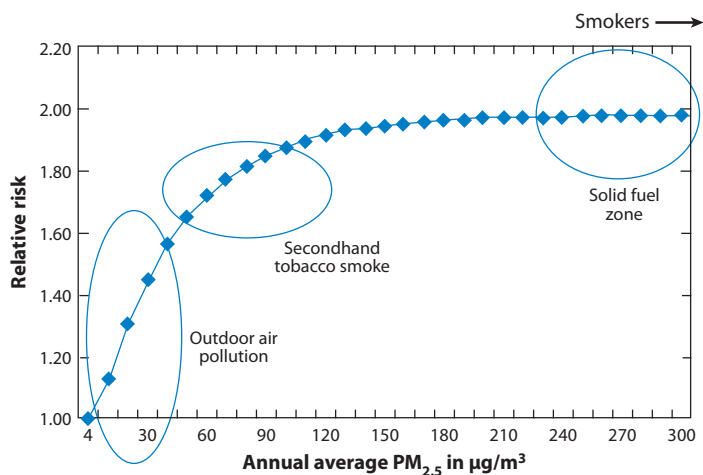


Figure 3 Relative exposure intensities of various forms of biomass fuel combustion, with associated risk of ischemic heart disease. PM_{2.5}, particles less than 2.5 µg in diameter. Based on References 126, 165, 211.

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 CO₂, 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 CO₂ 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.

PM₁₀: 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 CO₂, 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.

CO₂ 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 PM₁₀ 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 NO_x 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 CO₂, 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 CO₂ 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

ivers. 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 CO₂ 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

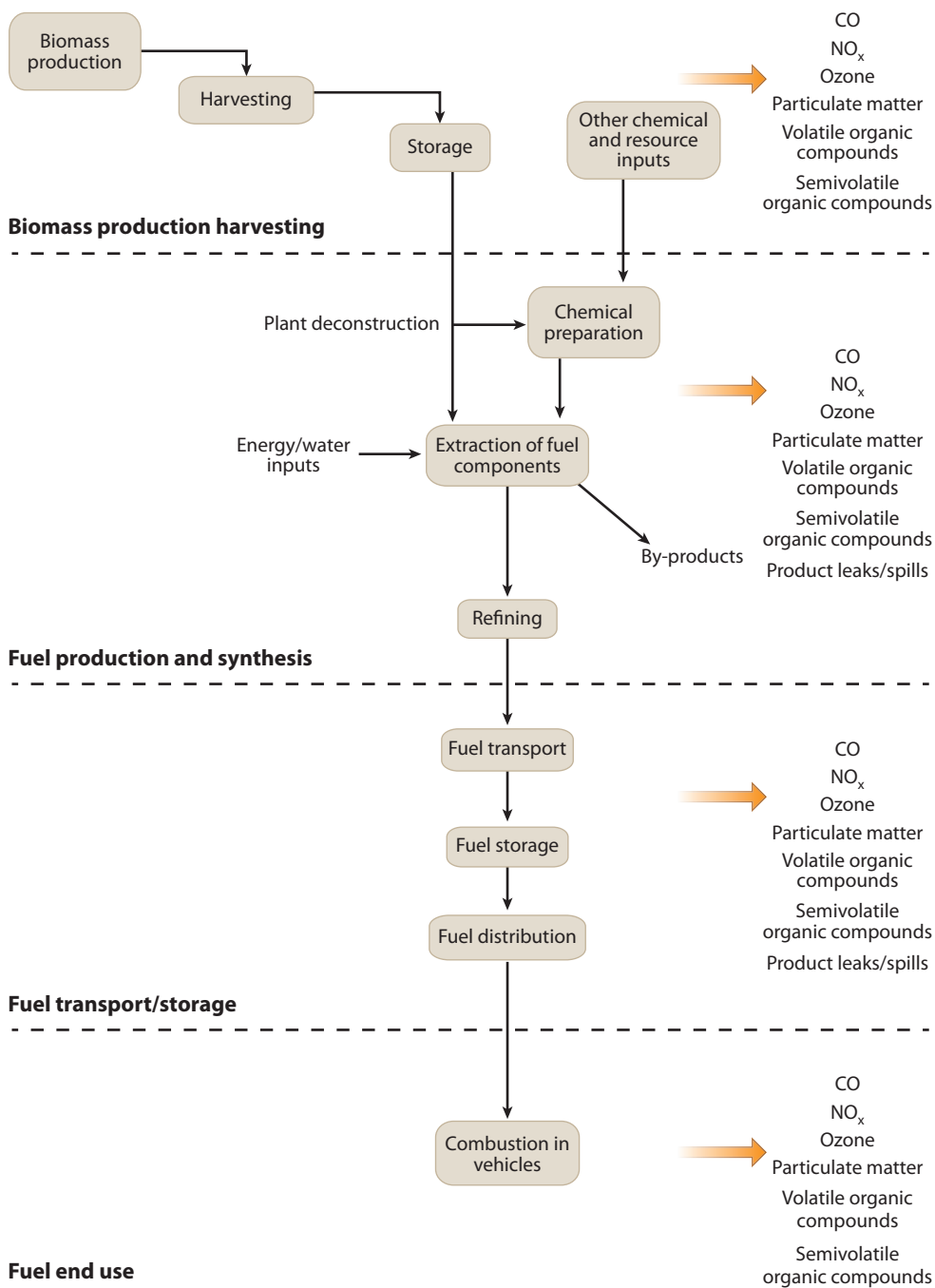


Figure 4

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 terror-

ist 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 emis-

sions 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 CO₂ 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 CO₂, 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, CO₂ 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-CO₂ 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)

²See 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.

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Contents

Symposium: Developmental Origins of Adult Disease

Commentary on the Symposium: Biological Embedding, Life Course Development, and the Emergence of a New Science
Clyde Hertzman 1

From Developmental Origins of Adult Disease to Life Course Research on Adult Disease and Aging: Insights from Birth Cohort Studies
Chris Power, Diana Kuh, and Susan Morton 7

Routine Versus Catastrophic Influences on the Developing Child
Candice L. Odgers and Sara R. Jaffee 29

Intergenerational Health Responses to Adverse and Enriched Environments
Lars Olov Bygren 49

Epidemiology and Biostatistics

Commentary on the Symposium: Biological Embedding, Life Course Development, and the Emergence of a New Science
Clyde Hertzman 1

From Developmental Origins of Adult Disease to Life Course Research on Adult Disease and Aging: Insights from Birth Cohort Studies
Chris Power, Diana Kuh, and Susan Morton 7

Causal Inference in Public Health
Thomas A. Glass, Steven N. Goodman, Miguel A. Hernán, and Jonathan M. Samet 61

Current Evidence on Healthy Eating
Walter C. Willett and Meir J. Stampfer 77

Current Perspective on the Global and United States Cancer Burden Attributable to Lifestyle and Environmental Risk Factors
David Schottenfeld, Jennifer L. Beebe-Dimmer, Patricia A. Buffler, and Gilbert S. Omenn 97

Annu. Rev. Public. Health. 2013.34:159-188. Downloaded from www.annualreviews.org by Prof. Kirk R. Smith on 03/31/13. For personal use only.

The Epidemiology of Depression Across Cultures <i>Ronald C. Kessler and Evelyn J. Bromet</i>	119
Routine Versus Catastrophic Influences on the Developing Child <i>Candice L. Odgers and Sara R. Jaffee</i>	29
Intergenerational Health Responses to Adverse and Enriched Environments <i>Lars Olov Bygren</i>	49
Environmental and Occupational Health	
Intergenerational Health Responses to Adverse and Enriched Environments <i>Lars Olov Bygren</i>	49
Causal Inference Considerations for Endocrine Disruptor Research in Children’s Health <i>Stephanie M. Engel and Mary S. Wolff</i>	139
Energy and Human Health <i>Kirk R. Smith, Howard Frumkin, Kalpana Balakrishnan, Colin D. Butler, Zoë A. Chafe, Ian Fairlie, Patrick Kinney, Tord Kjellstrom, Denise L. Mauzerall, Thomas E. McKone, Anthony J. McMichael, and Mycle Schneider</i>	159
Links Among Human Health, Animal Health, and Ecosystem Health <i>Peter Rabinowitz and Lisa Conti</i>	189
The Worldwide Pandemic of Asbestos-Related Diseases <i>Leslie Stayner, Laura S. Welch, and Richard Lemen</i>	205
Transportation and Public Health <i>Todd Litman</i>	217
Public Health Practice	
Implementation Science and Its Application to Population Health <i>Rebecca Lobb and Graham A. Colditz</i>	235
Promoting Healthy Outcomes Among Youth with Multiple Risks: Innovative Approaches <i>Mark T. Greenberg and Melissa A. Lippold</i>	253
Prospects for Tuberculosis Elimination <i>Christopher Dye, Philippe Glaziou, Katherine Floyd, and Mario Raviglione</i>	271
Rediscovering the Core of Public Health <i>Steven M. Teutsch and Jonathan E. Fielding</i>	287

Social Environment and Behavior

Routine Versus Catastrophic Influences on the Developing Child <i>Candice L. Odgers and Sara R. Jaffee</i>	29
HIV Prevention Among Women in Low- and Middle-Income Countries: Intervening Upon Contexts of Heightened HIV Risk <i>Steffanie A. Strathdee, Wendee M. Wechsberg, Deanna L. Kerrigan, and Thomas L. Patterson</i>	301
Scaling Up Chronic Disease Prevention Interventions in Lower- and Middle-Income Countries <i>Thomas A. Gaziano and Neba Pagidipati</i>	317
Stress and Cardiovascular Disease: An Update on Current Knowledge <i>Andrew Steptoe and Mika Kivimäki</i>	337
The Impact of Labor Policies on the Health of Young Children in the Context of Economic Globalization <i>Jody Heymann, Alison Earle, and Kristen McNeill</i>	355
Commentary on the Symposium: Biological Embedding, Life Course Development, and the Emergence of a New Science <i>Clyde Hertzman</i>	1
From Developmental Origins of Adult Disease to Life Course Research on Adult Disease and Aging: Insights from Birth Cohort Studies <i>Chris Power, Diana Kuh, and Susan Morton</i>	7
Intergenerational Health Responses to Adverse and Enriched Environments <i>Lars Olov Bygren</i>	49
Promoting Healthy Outcomes Among Youth with Multiple Risks: Innovative Approaches <i>Mark T. Greenberg and Melissa A. Lippold</i>	253
The Behavioral Economics of Health and Health Care <i>Thomas Rice</i>	431

Health Services

Reducing Hospital Errors: Interventions that Build Safety Culture <i>Sara J. Singer and Timothy J. Vogus</i>	373
Searching for a Balance of Responsibilities: OECD Countries' Changing Elderly Assistance Policies <i>Katherine Swartz</i>	397

Strategies and Resources to Address Colorectal Cancer Screening Rates and Disparities in the United States and Globally <i>Michael B. Potter</i>	413
The Behavioral Economics of Health and Health Care <i>Thomas Rice</i>	431
Scaling Up Chronic Disease Prevention Interventions in Lower- and Middle-Income Countries <i>Thomas A. Gaziano and Neha Pagidipati</i>	317

Indexes

Cumulative Index of Contributing Authors, Volumes 25–34	449
Cumulative Index of Article Titles, Volumes 25–34	454

Errata

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