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Impacts of Coal Use on Health

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Keywords

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Abstract

This article reviews evidence for the public health impacts of coal across the extraction, processing, use, and waste disposal continuum. Surface coal mining and processing impose public health risks on residential communities through air and water pollution. Burning coal in power plants emits more nitrogen oxides, sulfur dioxide, particulate matter, and heavy metals per unit of energy than any other fuel source and impairs global public health. Coal ash disposal exposes communities to heavy metals and particulate matter waste. Use of coal in domestic households causes public health harm concentrated in developing nations. Across the coal continuum, adverse impacts are disproportionately felt by persons of poor socioeconomic status, contributing to health inequities. Despite efforts to develop renewable energy sources, coal use has not declined on a global scale. Concentrated efforts to eliminate coal as an energy source are imperative to improve public health and avert serious climate change consequences.

1. INTRODUCTION

Coal is a sedimentary rock consisting primarily of carbonaceous material formed from plant remains subjected to geological heat and pressure over millions of years (122). Coal is combustible and has been used as a fuel source for centuries (122). Since the eighteenth century, coal has been used on a large scale for home cooking and heating, industry, and electricity generation. Coal has been plentiful in the United States and other places around the world, contributing to modern global economic development. In more recent years, public health and environmental harms linked to coal have become apparent, particularly the contributions of coal combustion pollutants to climate change, adverse air and water quality, and human morbidity and mortality (see **Table 1** for a summary).

This article reviews evidence for the impacts of coal use on human health. We attend to epidemiological, laboratory, and environmental studies conducted in the United States and globally. Our review focuses not only on coal combustion for electricity generation, but also on coal as a home fuel source in the developing world. Beyond coal combustion, we consider public health research related to the entire coal use continuum, including mining, transportation, processing, and waste disposal (see **Figure 1**). An important thread integrating this review is the consideration of health inequities, as coal production, use, and waste disposal have disproportionate impacts on socioeconomically disadvantaged communities in the United States and around the world.

For comparative purposes, we address briefly studies of environmental and public health impacts of alternative fuel sources, including natural gas, petroleum, nuclear power, and renewables. We focus our review on impacts of coal use on population health and do not attempt to summarize the large and important literature on occupational health effects experienced by coal miners.

2. GLOBAL POLITICAL CONTEXT

Coal accounts for about 38% of electricity generation worldwide (75) and about 28% in the United States (28). China and the United States far outpace the rest of the world by accounting for 58% of the world's coal electricity generation (74). In 2016, coal accounted for approximately 44% of worldwide CO_2 emissions, exceeding both oil (∼35%) and natural gas (∼20%) (74). Thus, coal is a major contributor to climate change.

Table 1 Summary of public health and environmental consequences of the coal use continuum

Consequences	Extraction and processing	Use		Waste
		Power generation	Household	
Public health	(*a*) Respiratory illness, cancer, cardiovascular disease, kidney disease, poor birth outcomes, poor quality of life, mental health problems, mortality	(*c*) Respiratory illness, cancer, cardiovascular disease, preterm delivery, adult and infant mortality	(*e*) Fluorosis, arsenism, selenosis, lung cancer, adverse child development	(*g*) Child development
Environmental	(*b*) Air, soil, and surface water and groundwater pollution, including elevated PM, ambient silica, PAHs, cleaning chemicals	(*d*) Air pollution including NOx, SO_2, PM, PAHs, metals	(*f*) Air pollution, including metals and PM	(*h*) Coal ash soil and water contamination with heavy metals, radioactive elements, PAHs
	(*i*) Climate change			

Abbreviations: NOx, nitrogen oxides; PAHs, polycyclic aromatic hydrocarbons; PM, particulate matter; SO_2, sulfur dioxide.

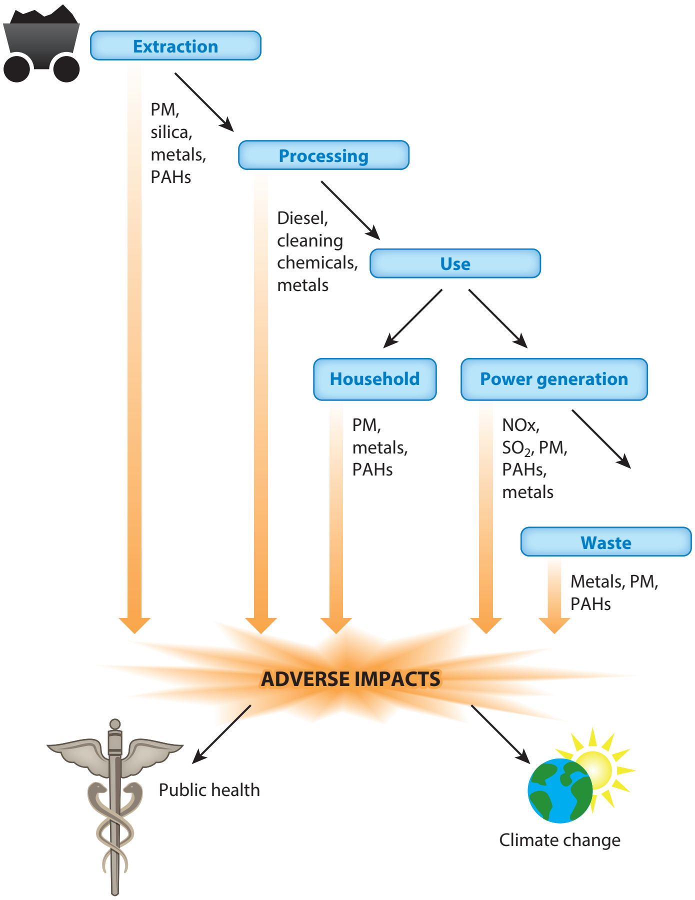

Figure 1

The coal use continuum and its impacts. Abbreviations: NOx, nitrogen oxides; PAHs, polycyclic aromatic hydrocarbons; PM, particulate matter; SO_2, sulfur dioxide.

Efforts have been undertaken in the United States and globally to reduce dependence on coal to combat air pollution and climate change. The Paris Agreement reached by the United Nations in 2016 (138) and the Clean Power Plan implemented by the United States in 2015 (27) are two key examples. These examples are perhaps most notable because of initiatives since early 2017 by the US government to withdraw from these agreements. The US Environmental Protection Agency (EPA), for example, has rescinded the Clean Power Plan and replaced it with the Affordable Clean Energy (ACE) rule (142). According to the EPA, the ACE is intended to prolong the use of coal for power generation and to disinvest in coal alternatives, including natural gas and renewable fuel sources (140). This position stands in contrast to the 2018 special report from the United Nations Intergovernmental Panel on Climate Change, which emphasizes the critical need to curtail the use of fossil fuels immediately to prevent catastrophic global warming consequences (61). Not surprisingly, efforts to prolong coal dependence in the United States have been met with resistance by environmental, scientific, and medical organizations (27, 37, 92).

The United States currently stands at odds with many policy developments around the world. The picture, however, is complicated, with simultaneous evidence of efforts to reduce coal use

in significant parts of the world but limited evidence to date of real global-wide impact. Many European nations have announced plans to phase out coal-fired power completely by the 2030s or sooner (13, 72). Spain closed most of its coal mines at the end of 2018 (44) and has committed to eliminating both nuclear and coal power by 2030 and transitioning to a completely renewable electricity system (104). India's national energy policy is multifaceted and includes commitments to reduce fossil-fuel emissions by 33–35% by 2030 using 2005 as a baseline while increasing non–fossil fuel power production to 40% over the same time period (72). Despite these commitments, however, India continues to invest in coal-fired power plants (126).

China has stated its commitment to achieve peak CO_2 emissions by 2030 or sooner (135). China also committed to lower CO_2 emissions per unit of gross domestic product by 60–65% using baseline 2005 levels while increasing the share of non–fossil fuel consumption to about 20% for primary energy usage (97). Some have argued that 2013 marked the end of peak coal in China owing to changes in heavy industry and proactive energy policies such that the country will no longer be dependent on coal consumption (117), a position reiterated in a subsequent article (116). However, this prediction has not yet borne out as coal use in China increased in 2017 and 2018 relative to prior years (46). There are also indications that China, while attempting to reduce coal use domestically, is heavily investing in new coal power plant construction in other parts of the world (62).

During the 2017 UN Climate Change Conference, more than 20 nations, including many in Europe as well as Canada, Mexico, and others, committed to phasing out traditional coal power (136). However, at the 2018 UN Climate Change Conference, efforts to confirm and expand these commitments were met with resistance, primarily from the United States, Australia, Russia, Brazil, Kuwait, and Saudi Arabia (48). Despite recognition of the need to reduce the environmental impacts of burning coal, coal remains a key resource in economic development efforts in China, India and many other countries (73). World coal consumption is not declining and reached an all-time peak in 2018, the most recent year of data at the time of this writing, as measured by megawatt power production (33). As measured by tons of coal mined, production peaked in 2014 but still shows no appreciable decline since then and increased between 2017 and 2018 (30). Given this current context, a review of the public health impacts of coal across the use continuum seems timely and necessary.

3. COAL MINING AND PROCESSING

Before coal can be burned at a power plant, it must first be mined, processed, and transported. Coal mining occurs in various forms, divided into underground and surface mining. Underground mining includes longwall and room and pillar techniques. Surface mining includes open pit, strip mining, highwall, and mountaintop removal. Public health concerns generally focus on surface more than underground mining owing to the exposed nature of surface mining practices relative to nearby human settlements. The next sections offer an in-depth case study on the public health impacts of one relatively well-investigated form of surface mining.

3.1. Case Study: Mountaintop Removal

Research evidence from the United States and other countries indicates that surface coal mining generates air, soil, and water pollution and likely harms the health of nearby populations (3, 10, 22, 57, 59, 96, 112, 150). Much of the research in the United States has been conducted on a form of surface coal mining that takes place in Appalachia called mountaintop removal (MTR) (see the sidebar titled Mining in Appalachia).

MINING IN APPALACHIA

Appalachia is a mountainous, forested, largely rural region in the eastern United States that stretches from southern New York to northeastern Mississippi. The Central Appalachian portion of the region is characterized by chronically poor economic conditions for its residents. The environmental impacts of MTR are thus concentrated in a population that already experiences other socioeconomic disadvantages. MTR has occurred in the region since the 1970s but became widespread, and the dominant form of land use change for the region (9), beginning in the 1990s.

As the name suggests, MTR involves the physical reduction of mountains to reach and extract buried coal seams (23, 141). The process includes clearcutting forests, usually burning the trees or dumping them into adjacent valleys. Then, explosives and heavy machinery remove up to 800 feet of mountain elevation to reach the coal. The rock and soil debris, called overburden, is dumped over the valley sides where it permanently buries headwater streams. The process takes place in Virginia, West Virginia, Kentucky, and Tennessee over a footprint of about 18,000 square miles. In the steep terrain and narrow river valleys of the Central Appalachians, human settlements are typically located on the valley bottoms, while the mining activities take place overhead. Approximately 1.2 million people live in counties where MTR occurs. To date, MTR has destroyed more than 500 mountains and buried more than 2,000 stream miles (4, 113). Water flowing from mining sites is contaminated with sulfates, metals, and other impurities and remains contaminated decades after mining at a site has ended (96).

3.2. Environmental Impacts From Coal Mining and Processing

After the coal is dug from the mountain, it is transported by conveyor belt or truck to processing centers, where the coal is crushed and chemically washed before being loaded onto trucks, trains, and barges for shipment to power plants. The washing generates billions of gallons of water contaminated with metals, other noncombustible material, and cleaning chemicals; this water is subsequently stored in surface impoundments or injected underground. Coal transportation vehicles typically depend on diesel fuel, contributing to local air pollution. Coal cleaning formulas are proprietary but contain numerous chemicals; it was one of these chemicals [4-methylcyclohexanemethanol (MCHM)] that leaked into the Charleston, West Virginia, water supply in 2014, disrupting drinking water access to 300,000 people (38). Evidence has shown that private wells are sometimes impaired with contaminated water from coal-processing activities (110, 131), and drinking water treatment violations are several times more common in MTR areas of West Virginia compared with nonmining areas (56).

3.3. Health Impacts of MTR from Epidemiological Studies

Epidemiological studies have reported associations between multiple public health outcomes and coal mining in general, and MTR in particular (refer to **Table 1**, cell *a*). Persons who live near surface mining operations experience significantly higher rates of morbidity and/or mortality from cardiovascular disease (32), kidney disease (51), respiratory disease (51, 59), dental disease (53), and cancer (1, 22, 60). Birth defects are more common among mothers residing in MTR areas compared with other parts of the Central Appalachians (2). Self-reported health-related quality of life and mental health are also significantly poorer in association with MTR (17, 24, 150). These associations persist after statistical control for smoking and obesity rates, poverty, education, occupational exposure, and other covariates. Some studies used ecological designs with data at the

county level (49) or block group (55), and others have been correlational studies using person-level data (50). Studies employing more sophisticated methodological approaches such as propensity scoring (59), difference-in-difference analysis (58), or spatial modeling (55) also report significant associations between mining activity and poor public health. Evidence has shown dose–response effects, with the most severe health problems found in areas where either (*a*) MTR occurs, with intermediate outcomes in areas with other types of mining and the best outcomes in areas where mining is absent (150), or (*b*) mining is heaviest as measured by tons of production compared with areas with less production (51). When considered from a public health perspective, the economic benefits of the Appalachian coal mining industry (dollars generated directly and indirectly from industry activities) are outweighed by its costs (mining-associated premature mortality) (52).

3.4. Health Impacts of MTR from Laboratory and Environmental Studies

In addition to epidemiological studies, laboratory and environmental studies have identified problems associated with MTR. Outdoor particulate matter samples collected from residential mining communities have been shown to induce cardiac and vascular dysfunction in rats (84, 108). The mining dust is a complex mixture but contains high levels of respirable silica (86), which suggests an origin from the removal of rock overburden to reach coal. Silica exposure is known to cause lung cancer, chronic obstructive pulmonary disease, cardiovascular disease, and kidney disease (109), which epidemiological studies have documented occur at elevated rates in mining communities. MTR dust also promotes the progression of cancer in human lung cells (98). West Virginia mining communities experience significantly higher ultrafine particle counts in ambient air (87), and particulate matter includes elevations in polycyclic aromatic hydrocarbons (PAHs) and a variety of inorganic constituents suggestive of crustal origin (86) (**Table 1**, cell *b*).

3.5. Public Health Impacts from Coal Mining Worldwide

Evidence for public health effects from coal mining in other parts of the United States is much more limited (54). MTR is practiced in strict form only in Appalachia, and it may be that the topography, population density around mining sites, other population characteristics, or the mountain-based mining practices themselves account for observed relationships. But conclusions are difficult given a general absence of information on which public health effects may result from mining practices in other parts of the country.

Globally, surface coal mining is associated with a number of poor environmental and public health indicators (**Table 1**, cells *a* and *b*). Perhaps the earliest example in the scientific literature is a study by Temple & Sykes (132), which showed increases in new episodes of asthma presenting to a medical practice after the opening of a surface coal mine in Great Britain. Other studies in Great Britain have suggested that respiratory problems in children are related to surface coal mining (15, 114), but null findings have also been reported (67).

Studies in China indicated that surface coal mining was related to a higher occurrence of neural tube birth defects (95) and that areas proximate to coal mining have elevated soil pollution (69). Cancer mortality has been documented in association with coal mining in Spain (36). A study in Turkey revealed that children living near surface coal mining had elevated blood cadmium and lead levels (147), and another in Brazil found elevations in trace elements in children's urine samples (121). Studies in other countries including Brazil, Colombia, and India have documented effects on animal populations as bioindicators (11, 43, 149) or have demonstrated that surface coal mining generates local air pollution (41, 70).

Mishra (102) conducted 300 interviews in Angul-Talcher, one of the major industrial zones in India. Five villages were 3.5 km or less from mines, and two were approximately 47 km away. In brief, Mishra (102) found that 90% of households in the mining villages in the past year reported health problems compared with 52% in nonmining villages. Symptoms were invariant by gender, and villages closest to mining activity reported the highest number of health problems. These findings support a broader literature conducted in India regarding airborne pollutants produced by coal mining, combustion, and transport (41, 42).

In sum, although direct mechanistic links are not well understood, the weight of epidemiological and environmental evidence from studies around the world points to the high likelihood of public health harm imposed by surface coal mining activities [see Cortes-Ramirez et al. (25) for another review]. Harm likely occurs through air, soil, and water exposure routes and may involve numerous chemical exposures rather than a single chemical of concern.

4. COAL AS A FUEL SOURCE

4.1. Coal Power Plant Combustion and Public Health

Per kilowatt hour, coal combustion generates more particulate matter, heavy metals, sulfur dioxide, and nitrogen oxides than does natural gas or other fuels (39, 78, 100, 106) (**Table 1**, cell *d*). In turn, coal combustion pollutants contribute to widespread organ system pathology (7, 34, 106, 119, 145) and to substantially greater mortality and morbidity compared with other fuel sources (99). Particulate matter emissions alone (excluding gaseous pollutants) from coal-fired power plants are estimated to be responsible for as many as 52,000 premature deaths annually in the United States (5, 16) (**Table 1**, cell *c*). An estimate for China is 670,000 premature annual deaths (79), and for India, 80,000–115,000 (12). Air pollution now affects most of the world's population; the most acute exposures occur in cities, and declines in air quality are most pronounced in developing countries (144).

Huang et al. (68) estimated that coal combustion was the dominant source of air pollution during wintertime high pollution days in Beijing (traffic pollution was dominant during low pollution days). Laden et al. (89) and Ito et al. (77) used source apportionment strategies to identify positive associations between coal combustion and daily mortality in cities in the United States. The retirement of coal and oil plants in California has been linked to reductions in preterm births (19). A national source apportionment study found that particulate matter from coal combustion was the dominant source contributing to ischemic heart disease mortality (133). Internationally, coal combustion has been linked to higher mortality in Spain (111) and China (21) and to numerous poor health outcome indicators in India (12, 45).

A systematic review of 113 peer-reviewed publications by Kravchenko & Lyerly (85) concluded that living near coal power plants was associated with numerous adverse public health impacts, including all-cause and premature mortality, respiratory disease and lung cancer, cardiovascular disease, poorer child health, and higher infant mortality. Pollutants linked to health effects included sulfur dioxide and nitrogen dioxide, particulate matter at fine (aerodynamic diameter $<2.5\ \mu m$) and ultrafine (≤ 100 nm) scales, and metals such as arsenic, chromium, and others. Coal combustion likely constitutes the single largest contributing factor to adverse public health across the coal use continuum.

4.2. Domestic Household Coal Use

In addition to its industrial-scale use for electricity and power generation, coal is still a common fuel source for heating and cooking in individual households. The pollution created by household

COAL AND HEALTH DISPARITIES

Across all stages of the coal continuum, coal use has disproportionately adverse impacts on vulnerable populations, contributing to global health inequities. MTR occurs in Appalachian communities that have among the poorest socioeconomic conditions in the United States. Burning coal in individual households occurs primarily among the poorest residents of developing nations. Coal-fired power plants are located disproportionately in neighborhoods of color and in low-socioeconomic-status communities, and coal waste disposal often occurs proximate to the power plants. The electricity produced from power plants is transferred great distances over power lines, but the externalities are concentrated among the most vulnerable members of society.

burning of solid fuels, including coal, affects about 3 billion people worldwide; the majority of these households are in China and India (125). Household coal use has profound health disparity consequences because it occurs mostly among poorer rural households in developing countries. These households often burn coal inefficiently, with poorly vented combustion devices, leading to significant pollution exposures particularly among women and children (129). Many adverse health consequences caused by household coal utilization in China have been reported, including endemic fluorosis, arsenism, selenosis, lung cancer, and adverse effects on child development (20) (**Table 1**, cell *e*) (see the sidebar titled Coal and Health Disparities).

The International Agency for Research on Cancer has classified emissions from household coal combustion as a Group 1 human carcinogen (71), suggesting little dispute about its serious health consequences. A meta-analysis of 25 case-control studies by Hosgood et al. (65) in all regions of the world found increased odds for lung cancer [odds ratio (OR) = 2.15, 95% confidence interval (CI) (1.61–2.89)] in households that burned coal. Some areas of China provide good case studies of lung cancer risks from coal combustion exposure, especially in Xuan Wei County (XWC), in Yunnan Province, where the lung cancer rate is approximately 5 times greater than the Chinese national average and, in some cases, 24 times greater (105). In XWC, an anomaly exists where female residents, who are largely nonsmokers, experience the highest lung cancer rates in China, similar to the rate of males, who are primarily smokers. High lung cancer risk in XWC females cannot be attributed to occupational exposure, tobacco smoking, or secondhand tobacco exposure (81, 91), but rather occurs through the use of "smoky coal" for cooking and heating in households without chimneys (105, 125). Lung cancer risk is much greater in association with the use of domestic smoky coal (i.e., bituminous) relative to nonsmoky coal (i.e., anthracite) (8). Research by Mumford et al. (105) demonstrated that domestic smoky coal use was highly correlated with lung cancer owing to exposure to high concentrations of mutagenic/carcinogenic PAHs (**Table 1**, cell *f*). More recent research by Lan et al. (91) suggests significant risk for lung cancer among smoky coal users, with ORs ranging from 1.1 to 27.0 compared with smokeless coal and wood users. Differences persisted after adjustment for multiple confounders (e.g., amount of coal used, time spent indoors, type of ventilation, tobacco exposure). These exposures are believed to cause mutations in the p53 tumor suppression gene and K-ras oncogene (26, 82). For a review of published data on these mutations, see Keohavong et al. (81).

5. COAL WASTE DISPOSAL

Coal combustion in power plants generates waste by-products, primarily coal ash. Coal ash contains radioactive elements, minerals, and heavy metals such as arsenic, mercury, cadmium, and lead (**Table 1**, cell *h*). Approximately 80% of coal ash is fly ash; it is respirable and primarily glass in

chemical structure (80). Coal ash is typically stored in impoundments containing a mix of fine powder and sludge, often located near residential communities. Approximately 140 million tons of coal ash are generated annually in the United States (115). In 2018, the US EPA finalized a rule that weakened groundwater monitoring requirements and extended the life of some existing impoundments (29). Coal ash spills such as the one in Kingston, Tennessee, in 2008 can release high levels of toxic elements and radioactivity into the environment (120). Research has documented increased health problems for children who reside near coal ash impoundments (123, 148) (**Table 1**, cell *g*). Kravchenko & Lyerly (85) reported water and soil contamination from coal ash impoundments as well as high levels of PAHs and numerous metals, including mercury, arsenic, cadmium, chromium, lead, nickel, zinc, and others; these coal ash impoundments are disproportionately more likely to be located near low-income communities.

In India, sources of coal are of generally poor quality, with low calorific value and high ash content, and the poorest coal quality is supplied to domestic power plants (103). Although natural radionuclides in coal samples are approximately equivalent as those found in ambient soils, combustion enriches the radionuclides by factors of 2–5 in fly ash. Mishra (103) determined that fly-ash dumps contain the highest radiation doses and therefore pose significant health risks to populations surrounding coal-fired power plants.

6. COMPARATIVE PUBLIC HEALTH RISKS FROM OTHER FUEL SOURCES

We offer brief comparative remarks concerning evidence for public health impacts from use of other noncoal fuel sources. We consider fuel use for power generation but not transportation (e.g., diesel). We do not attempt a full description of these effects, and we again do not address occupational exposures, but offer these comments to briefly compare and contrast effects with those of coal use.

6.1. Natural Gas

Natural gas has become the largest single source of electricity generation in the United States, accounting for 35% in 2018 (28). Globally, natural gas constitutes about 23% of electricity generation (75). Natural gas is 70–90% methane (107); its combustion generates less carbon dioxide, sulfur, nitrogen oxides, heavy metals, and particulates relative to coal. However, when considering the entire production continuum, natural gas may impose a larger greenhouse gas cost than coal, owing to emissions of methane and other hazardous air pollutants including PAHs, BTEX (benzene, toluene, ethylbenzene, and xylenes), and other volatile organic compounds from production, processing, and distribution activities (40, 66).

The recent rise of natural gas as a major energy source in the United States corresponds to the rise of unconventional shale gas development or hydraulic fracturing (i.e., fracking). A number of public health concerns have been raised with respect to water and air pollution from fracking activities (18). Empirical evidence on public health impacts is still limited (146), although a growing number of studies report associations between exposure to fracking activities and adverse health effects (101, 118, 143).

6.2. Nuclear

Nuclear energy accounts for approximately 19% of US electricity generation (28) and about 10% of global electricity generation (75). Risks associated with the use of nuclear fuel include

those associated with extraction and processing, transportation, use in power plants, power plant failures, and waste disposal. Uranium mining occurs on only a small scale in the United States, as most uranium used in nuclear plants is imported (mostly from Canada, Kazakhstan, Australia, and Russia). Much of the former US uranium mining took place in the Southwest in proximity to Navajo populations, and evidence has shown that Navajo water sources near abandoned mine sites have elevated levels of arsenic and uranium (63). Evidence has also demonstrated inhalation exposure to arsenic and uranium near mining sites (47). A review concluded that residence near former uranium mining sites was associated with kidney disease, hypertension, and other chronic illnesses for Native American populations (94).

Regarding the use of nuclear fuel, a meta-analysis concluded that leukemia incidence and mortality rates were elevated for children living near nuclear facilities (6), which may result from prenatal exposures (35); explanations on causes are speculative however. Accidents such as those at Three Mile Island in 1979, Chernobyl in 1986, and Fukushima in 2011 have raised concerns about impacts on cancer risks. Management of nuclear waste is an ongoing controversy as long-term storage is required with uncertain safety parameters over time.

6.3. Petroleum

Petroleum in liquid and solid form is used for only 0.6% of US electricity generation (79) and about 3.3% of global electricity generation (75). Petroleum combustion generates air pollutants including carbon dioxide, carbon monoxide, nitrogen oxides, sulfur oxides, particulates, PAHs, and metals (129). Transportation-related health consequences have been well studied, but human health impacts from petroleum-based electricity generation have not; one might expect the effects to be similar to those associated with coal on a smaller scale.

6.4. Renewables

Renewables including hydropower, biomass, solar, wind, and geothermal account for approximately 17% of US electricity generation (28) and 25% of global electricity generation (75). Hydroelectric power does not involve combustion and is considered safe from a public health perspective, although dams can have major environmental impacts, including obstructing fish migrations, changing water temperature and flow, and flooding natural areas or agricultural lands. Potential risks also exist with respect to dam failures or infectious disease exposures (129). Biomass burning (i.e., wood, landfill gas, and solid waste) for household or commercial power generation has been linked to serious human health consequences (93), with one estimate projecting 40,000 additional annual deaths in Europe (128). Wind farms have been linked to noise-related sleep disturbance and reduced quality of life, although these drawbacks are minor compared with population health and environmental effects linked to fossil fuel use (83). Wind and solar farms can adversely impact wildlife populations and natural ecosystems (88), although conventional fuels carry these adverse impacts as well, possibly on larger scales (130, 134).

6.5. Summary of Alternative Fuels

In sum, it is clear that no fuel source for power generation is entirely benign, although renewables pose a substantially smaller risk potential for human health than do fossil fuels (14) with the possible exception of biomass fuels. Regardless of the fuel type, it is important to consider the entire use continuum, including extraction, processing, transportation, use, and waste disposal. When the entire continuum is considered, health costs of coal-based electricity exceed the value of the electricity that it generates, primarily because of population mortality costs from coal combustion (31).

7. PUBLIC HEALTH AND CLIMATE CHANGE

We do not attempt a full account of the public health impacts of climate change, as our focus is on the direct health effects of coal use; however, it is important to recognize the connection between coal and climate change (**Table 1**, cell *i*). The 2018 UN Intergovernmental Panel on Climate Change special report (61) provides a stark warning that greenhouse gas emissions must be quickly curtailed and reversed to avoid catastrophic climate changes. According to the International Energy Administration, coal combustion is responsible for more than 30% of the average global temperature increase since preindustrial times, the largest single source of this increase (76). Yet coal use is not in decline, and global population growth will place increasing demands on access to modern energy. The United Nations projects that the world population will rise by approximately 1% per year on average, from 7.6 billion in 2017 to 8.6 billion in 2030 (139). The fastest population growth will occur in Africa, intensifying the challenge to provide universal access to modern energy. By 2030, 78% of people in the world will be living either in Asia or in Africa. In addition, the percent of the world population living in urban areas is projected to rise from 55% in 2018 to 68% in 2050 (137). This increase equates to an extra 1.7 billion people added to the urban population over the next 32 years. This population growth and the urban transition will have significant implications for energy consumption. Urbanization accelerates demand for modern fuels, appliances, vehicle use, and construction materials, including energy-intensive products such as steel and cement (72).

Climate change left unchecked will have profound impacts on global population health (124, 144). These impacts include reductions in food security and access to natural resources, increases in infectious illness, heat-related morbidity and mortality, strains on health care and social services, reduced labor capacity, increased risks of armed conflict, and social instability from large-scale migration. The most vulnerable members of the human community will again face the greatest risks.

8. CONCLUSIONS AND RECOMMENDATIONS

Evidence is clear that coal use for home consumption or large-scale energy production comes at considerable public health and environmental cost. Where household combustion of coal may continue, there are steps that can be taken to mitigate risk. The literature suggests that the installation of ventilated stoves or chimneys reduced not only lung cancer risks (90), but also other respiratory conditions such as pneumonia (127). In addition, health improvements have been observed through the increased use of portable stoves (64). Nonetheless, although immediate improvements in the health of those who combust coal for household use may be realized from these actions, broader steps are necessary to reduce global human health and environmental risks.

The common use of coal for energy production was understandable when it was plentiful, technologically practical, had few competitors, and its harms were not recognized. Now, better alternatives are available that are not only economically competitive but also come with much lower externality costs. For climate change reasons alone, coal should be phased out of use for electricity generation as rapidly as possible. Its contraindications are compounded when we consider its direct adverse public health impacts during the extraction and processing, combustion, and waste disposal stages. These impacts have disproportionate consequences on populations that already face additional socioeconomic disadvantages. Although natural gas is environmentally superior to coal in the combustion phase, natural gas as a preferred alternative to coal in the fight against climate change is uncertain at best, owing to the high climate change impacts of methane emissions across the production continuum. Because of the growing threat of climate change, the continued development of safer renewable energy should be a top priority.

SUMMARY POINTS

1. Coal combustion creates more nitrogen oxides, sulfur dioxide, carbon dioxide, heavy metals, and particulate matter per unit of energy than do other fuel sources.
2. All phases of the coal use continuum (mining, processing, combustion, and waste disposal) create adverse public health and environmental impacts. Public health impacts include cancer, cardiovascular disease, respiratory disease, kidney disease, mental health problems, adverse birth outcomes, impaired child development, and others.
3. Coal across the use continuum impacts vulnerable populations disproportionately, contributing to health inequities.
4. We do not yet have clear evidence that coal use is in decline globally, despite its environmental and public health contraindications.
5. Natural gas may not be a superior alternative to coal for climate change mitigation. Renewable fuel sources are superior from environmental and public health perspectives, and an immediate and intensive switch to renewables for electricity generation is indicated.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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LITERATURE CITED

1. Ahern M, Hendryx M. 2012. Cancer mortality rates in Appalachian mountaintop coal mining areas. *J. Occup. Environ. Sci.* 1:63–70
2. Ahern M, Hendryx M, Conley J, Fedorko E, Ducatman A, Zullig KJ. 2011. The association between mountaintop mining and birth defects among live births in central Appalachia, 1996–2003. *Environ. Res.* 111:838–46
3. Aneja VP, Isherwood A, Morgan P. 2012. Characterization of particulate matter (PM_{10}) related to surface coal mining operations in Appalachia. *Atmos. Environ.* 54:496–501
4. Appalach. Voices. 2017. End mountaintop removal coal mining. *Appalachian Voices*. **http://appvoices.org/end-mountaintop-removal/**
5. Apt J. 2017. The other reason to shift away from coal: air pollution that kills thousands every year. *Scientific American*, June 7. **https://www.scientificamerican.com/article/the-other-reason-to-shift-away-from-coal-air-pollution-that-kills-thousands-every-year/**
6. 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
7. Balti EV, Echouffo-Tcheugui JB, Yako YY, Kengne AP. 2014. Air pollution and risk of type 2 diabetes mellitus: a systematic review and meta-analysis. *Diabetes Res. Clin. Pract.* 106:161–72
8. Barone-Adesi F, Chapman RS, Silverman DT, He X, Hu W, et al. 2012. Risk of lung cancer associated with domestic use of coal in Xuanwei, China: retrospective cohort study. *BMJ* 345:e5414

9. Bernhardt ES, Lutz BD, King RS, Fay JP, Carter CE, et al. 2012. How many mountains can we mine? Assessing the regional degradation of Central Appalachian rivers by surface coal mining. *Environ. Sci. Technol.* 46:8115–22
10. Bernhardt ES, Palmer MA. 2011. The environmental costs of mountaintop mining valley fill operations for aquatic ecosystems of the Central Appalachians. *Ann. N. Y. Acad. Sci.* 1223:39–57
11. Bharti S, Banerjee TK. 2011. Bioaccumulation of metals in the edible catfish *Heteropneustes fossilis* (Bloch) exposed to coal mine effluent generated at Northern Coalfield Limited, Singrauli, India. *Bull. Environ. Contam. Toxicol.* 87:393–98
12. Biswas T. 2013. Study estimates health impact of coal based power plants in India. *BMJ* 346:f2187
13. Bixel E. 2019. Overview: national coal phase-out announcements in Europe. *Europe Beyond Coal*. **https://beyond-coal.eu/wp-content/uploads/2019/10/Overview-of-national-coal-phase-out-announcements-October-2019.pdf**
14. Boffetta P, Cardis E, Vainio H, Coleman MP, Kogevinas M, et al. 1991. Cancer risks related to electricity production. *Eur. J. Cancer* 27:1504–19
15. Brabin B, Smith M, Milligan P, Benjamin C, Dunne E, Pearson M. 1994. Respiratory morbidity in Meyerside schoolchildren exposed to coal dust and air pollution. *Arch. Dis. Child.* 70:305–12
16. Caiazzo F, Ashok A, Waitz I, Yim SHL, Barrett SRH. 2013. Air pollution and early deaths in the United States. Part I: quantifying the impact of major sectors in 2005. *Atmos. Environ.* 79:198–208
17. Canu WH, Jameson JP, Steele EH, Denslow M. 2017. Mountaintop removal coal mining and emergent cases of psychological disorder in Kentucky. *Community Ment. Health J.* 53:802–10
18. Carpenter DO. 2016. Hydraulic fracturing for natural gas: impact on health and environment. *Rev. Environ. Health* 31:47–51
19. Casey JA, Karasek D, Ogburn EL, Goin DE, Dang K, et al. 2018. Retirements of coal and oil power plants in California: association with reduced preterm birth among populations nearby. *Am. J. Epidemiol.* 187:1586–94
20. Chen J, Liu G, Kang Y, Wu B, Sun R, et al. 2014. Coal utilization in China: environmental impacts and human health. *Environ. Geochem. Health* 36:735–53
21. Chen Y, Ebenstein A, Greenstone M, Li H. 2013. Evidence on the impact of sustained exposure to air pollution on life expectancy from China's Huai River policy. *PNAS* 110:12936–41
22. Christian WJ, Huang B, Rinehart J, Hopenhayn C. 2011. Exploring geographic variation in lung cancer incidence in Kentucky using a spatial scan statistic: elevated risk in the Appalachian coal-mining region. *Public Health Rep.* 126:789–96
23. Copeland C. 2015. *Mountaintop mining: background on current controversies*. Rep., Congr. Res. Serv., Washington, DC. **https://fas.org/sgp/crs/misc/RS21421.pdf**
24. Cordial P, Riding-Malon R, Lips H. 2012. The effects of mountaintop removal coal mining on mental health, well-being, and community health in central Appalachia. *Ecopsychology* 4:201–8
25. Cortes-Ramirez J, Naish S, Sly PD, Jagals P. 2018. Mortality and morbidity in populations in the vicinity of coal mining: a systematic review. *BMC Public Health* 18:721
26. DeMarini DM, Landi S, Tian D, Hanley NM, Li X, et al. 2001. Lung tumor KRAS and TP53 mutations in nonsmokers reflect exposure to PAH-rich coal combustion emissions. *Cancer Res.* 61:6679–81
27. EDF (Environ. Defense Fund). 2018. The Clean Power Plan. *Environmental Defense Fund*. **https://www.edf.org/clean-power-plan-resources**
28. EIA (Energy Inf. Adm.). 2019. What is U.S. electricity generation by energy source? *Energy Information Administration Frequently Asked Questions*. **https://www.eia.gov/tools/faqs/faq.php?id=427&t=3**
29. Eilperin J, Dennis B. 2018. EPA eases rules on how coal ash waste is stored across U.S. *Washington Post*, July 17. **https://www.washingtonpost.com/national/health-science/epa-eases-rules-on-how-coal-ash-waste-is-stored-across-the-us/2018/07/17/740e4b9a-89d3-11e8-85ae-511bc1146b0b_story.html?utm_term=.0399dda36e0a**
30. Enerdata. 2019. Global energy statistical yearbook 2019. *Enerdata Yearbook*. **https://yearbook.enerdata.net/coal-lignite/coal-world-consumption-data.html**
31. Epstein P, Buonocore JJ, Eckerle K, Hendryx M, Stout BM III, et al. 2011. Full cost accounting for the life cycle of coal. *Ann. N. Y. Acad. Sci.* 1219:73–98

32. Esch L, Hendryx M. 2011. Chronic cardiovascular disease mortality in mountaintop mining areas of central Appalachian states. *J. Rural Health* 27:350–57
33. Evans S, Pearce R. 2019. Mapped: the world's coal power plants. *Carbon Brief*, March 25. **https://www.carbonbrief.org/mapped-worlds-coal-power-plants**
34. Fagundes LS, Fleck Ada S, Zanchi AC, Saldiva PH, Rhoden CR. 2015. Direct contact with particulate matter increases oxidative stress in different brain structures. *Inhal. Toxicol.* 27:462–67
35. Fairlie I. 2014. A hypothesis to explain childhood cancers near nuclear power plants. *J. Environ. Radioact.* 133:10–17
36. Fernández-Navarro P, Garcia-Pérez J, Ramis R, Boldo E, López-Abente G. 2012. Proximity to mining industry and cancer mortality. *Sci. Total Environ.* 435–436:66–73
37. Friedman L. 2018. Cost of new E.P.A. coal rules: up to 1,400 more deaths a year. *New York Times*, Aug. 21. **https://www.nytimes.com/2018/08/21/climate/epa-coal-pollution-deaths.html?hp&action=click&pgtype=Homepage&clickSource=story-heading&module=first-column-region&region=top-news&WT.nav=top-news**
38. Gabriel T. 2014. Thousands without water after spill in West Virginia. *New York Times*, Jan 10. **https://www.nytimes.com/2014/01/11/us/west-virginia-chemical-spill.html**
39. 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
40. Garcia-Gonzales DA, Shonkoff SBC, Hays J, Jerrett M. 2019. Hazardous air pollutants associated with upstream oil and natural gas development: a critical synthesis of current peer-reviewed literature. *Annu. Rev. Public Health* 40:283–304
41. Ghose MK. 2007. Generation and quantification of hazardous dusts from coal mining in the Indian context. *Environ. Monit. Assess.* 130:35–45
42. Ghose MK, Majee SR. 2007. Characteristics of hazardous airborne dust around an Indian surface coal mining area. *Environ. Monit. Assess.* 130:17–25
43. Guerrero-Castilla A, Olivero-Verbel J, Marrugo-Negrete J. 2014. Heavy metals in wild house mice from coal-mining areas of Colombia and expression of genes related to oxidative stress, DNA damage and exposure to metals. *Mutat. Res. Genet. Toxicol. Environ. Mutagen.* 762:24–29
44. Guggenheim BL. 2018. Spain raises the bar in tackling carbon emissions with closure of coal mines. *South EU Summit*, Nov. 19. **https://www.southeusummit.com/europe/spain/spain-raises-the-bar-in-tackling-carbon-emissions-with-closure-of-coal-mines/**
45. Gupta A, Spears D. 2017. Health externalities of India's expansion of coal plants: evidence from a national panel of 40,000 households. *J. Environ. Econ. Manag.* 86:262–76
46. Hao F, Baxter T. 2019. China's coal consumption on the rise. *China Dialogue*, March 1. **https://www.chinadialogue.net/article/show/single/en/11107-China-s-coal-consumption-on-the-rise**
47. Harmon ME, Lewis J, Miller C, Hoover J, Ali AS, et al. 2017. Residential proximity to abandoned uranium mines and serum inflammatory potential in chronically exposed Navajo communities. *J. Expo. Sci. Environ. Epidemiol.* 27:365–71
48. Harvey F. 2018. 'We can more forward now': UN climate talks take significant step. *The Guardian*, Dec. 16. **https://www.theguardian.com/environment/2018/dec/16/katowice-we-can-move-forward-now-un-climate-talks-take-significant-step**
49. Hendryx M. 2009. Mortality from heart, respiratory, and kidney disease in coal mining areas of Appalachia. *Int. Arch. Occup. Environ. Health* 82:243–49
50. Hendryx M. 2013. Personal and family health in rural areas of Kentucky with and without mountaintop coal mining. *J. Rural Health* 29:S79–88
51. Hendryx M, Ahern M. 2008. Relations between health indicators and residential proximity to coal mining in West Virginia. *Am. J. Public Health* 98:669–71
52. Hendryx M, Ahern MA. 2009. Mortality in Appalachian coal mining regions: the value of statistical life lost. *Public Health Rep.* 124:541–50
53. Hendryx M, Ducatman AM, Zullig K, Ahern M, Crout R. 2012. Adult tooth loss for residents of US coal mining and Appalachian counties. *Community Dent. Oral Epidemiol.* 40:488–97
54. Hendryx M, Entwhistle J. 2015. Association between residence near surface coal mining and blood inflammation. *Extr. Ind. Soc.* 2:246–51

55. Hendryx M, Fedorko E, Anesetti-Rothermel A. 2010. A geographical information system-based analysis of cancer mortality and population exposure to coal mining activities in West Virginia, United States of America. *Geospat. Health* 4:243–56
56. Hendryx M, Fulk F, McGinley M. 2012. Public drinking water violations in mountaintop coal mining areas of West Virginia, USA. *Water Qual. Expo. Health* 4:169–75
57. Hendryx M, Higginbotham H, Ewald B, Connor LH. 2019. Air quality in association with rural coal mining and combustion in New South Wales Australia. *J. Rural Health* 35:518–27
58. Hendryx M, Holland B. 2016. Unintended consequences of the Clean Air Act: mortality rates in Appalachian coal mining communities. *Environ. Sci. Policy* 63:1–6
59. Hendryx M, Luo J. 2015. An examination of the effects of mountaintop removal coal mining on respiratory symptoms and COPD using propensity scores. *Int. J. Environ. Health Res.* 25:265–76
60. Hendryx M, O'Donnell K, Horn K. 2008. Lung cancer mortality is elevated in coal-mining areas of Appalachia. *Lung Cancer* 62:1–7
61. Hoegh-Guldberg OD, Jacob D, Taylor M, Bindi M, Brown S, et al. 2018. Impacts of 1.5°C global warming on natural and human systems. In *An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways*, *in the Context of Strengthening the Global Response to the Threat of Climate Change*, *Sustainable Development*, *and Efforts to Eradicate Poverty*, ed. V Masson-Delmotte, P Zhai, H-O Pörtner, D Roberts, J Skea, et al. Geneva: Intergov. Panel Climate Change (IPCC)–World Meteorol. Organ.
62. Hood M. 2018. China's unbridled export of coal power imperils climate goals. *Phys.org*, Dec. 5. **https://phys.org/news/2018-12-china-unbridled-export-coal-power.html**
63. Hoover J, Gonzales M, Shuey C, Barney Y, Lewis J. 2017. Elevated arsenic and uranium concentrations in unregulated water sources on the Navajo Nation, USA. *Expo. Health* 9:113–24
64. Hosgood HD 3rd, Chapman R, Shen M, Blair A, Chen E, et al. 2008. Portable stove use is associated with lower lung cancer mortality risk in lifetime smoky coal users. *Br. J. Cancer* 99:1934–39
65. Hosgood HD 3rd, 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
66. Howarth RW. 2014. A bridge to nowhere: methane emissions and the greenhouse gas footprint of natural gas. *Energy Sci. Eng.* 2:47–60
67. Howel D, Pless-Mulloli T, Darnell R. 2001. Consultations of children living near open-cast coal mines. *Environ. Health Perspect.* 109:567–71
68. Huang HF, Xing XL, Zhang ZZ, Qi SH, Yang D, et al. 2016. Polycyclic aromatic hydrocarbons (PAHs) in multimedia environment of Heshan coal district, Guangxi: distribution, source diagnosis and health risk assessment. *Environ. Geochem. Health* 38:1169–81
69. Huang X, Gordon T, Rom W, Finkelman R. 2006. Interaction of iron and calcium minerals in coals and their roles in dust-induced health and environmental problems. *Rev. Mineral. Geochem.* 64:153–78
70. Huertas JI, Huertas ME, Izquierdo S, Gonzalez ED. 2012. Air quality impact assessment of multiple open pit coal mines in northern Colombia. *J. Environ. Manag.* 93:121–29
71. IARC (Int. Agency Res. Cancer). 2010. *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans. Vol. 95. Household use of solid fuels and high temperature frying*. Rep., World Health Organ., IARC, Lyon, France. **https://monographs.iarc.fr/wp-content/uploads/2018/06/mono95.pdf**
72. IEA (Int. Energy Agency). 2017. Chapter 1: Introduction and scope. In *World energy outlook 2017*. Rep., IEA, Paris. **https://www.oecd-ilibrary.org/energy/world-energy-outlook-2017/introduction-and-scope_weo-2017-3-en**
73. IEA (Int. Energy Agency). 2017. *Key world energy statistics 2017*. Rep., IEA, Paris. **https://www.iea.org/publications/freepublications/publication/KeyWorld2017.pdf**
74. IEA (Int. Energy Agency). 2018. *Key world energy statistics 2018*. Rep., IEA, Paris. **https://doi.org/10.1787/key_energ_stat-2018-en**
75. IEA (Int. Energy Agency). 2019. Electricity statistics. *International Energy Agency*. **https://www.iea.org/subscribe-to-data-services/electricity-statistics**

76. IEA (Int. Energy Agency). 2019. *Global energy and CO_2 status report*. Rep., IEA, Paris. **https://www.iea.org/reports/global-energy-and-co2-status-report-2019**
77. Ito K, Christensen WF, Eatough DJ, Henry RC, Kim E, et al. 2006. PM source apportionment and health effects: 2. An investigation of intermethod variability in associations between source-apportioned fine particle mass and daily mortality in Washington, DC. *J. Expo. Sci. Environ. Epidemiol.* 16:300–10
78. Jaramillo P, Griffin WM, Matthews HS. 2007. Comparative life-cycle air emissions of coal, domestic natural gas, LNG, and SNG for electricity generation. *Environ. Sci. Technol.* 41:6290–96
79. Jing L. 2014. 670,000 smog-related deaths a year: the cost of China's reliance on coal. *South China Morning Post*, Nov. 5. **https://www.scmp.com/news/china/article/1632163/670000-deaths-year-cost-chinas-reliance-coal**
80. Jones T, Brown P, BéruBé KA, Wlodarczyk A, Shao L. 2010. The physicochemistry and toxicology of CFA particles. *J. Toxicol. Environ. Health A* 73:341–54
81. Keohavong P, Lan Q, Gao W. 2018. p53 and K-ras mutations in lung tissues and sputum samples of individuals exposed to smoky coal emissions in Xuan Wei County, China. *Mutat. Res. Genet. Toxicol. Environ. Mutagen.* 829–830:70–74
82. Keohavong P, Lan Q, Gao WM, Zheng KC, Mady HH, et al. 2005. Detection of p53 and K-ras mutations in sputum of individuals exposed to smoky coal emissions in Xuan Wei County, China. *Carcinogenesis* 26:303–8
83. Knopper LD, Ollson CA. 2011. Health effects and wind turbines: a review of the literature. *Environ. Health* 10:78
84. Knuckles T, Stapleton P, Minarchick V, Esch L, McCawley MA, et al. 2013. Air pollution particulate matter collected from an Appalachian mountaintop mining site induces microvascular dysfunction. *Microcirculation* 20:158–69
85. Kravchenko J, Lyerly HK. 2018. The impact of coal-powered electrical plants and coal ash impoundments on the health of residential communities. *N. C. Med. J.* 79:289–300
86. Kurth LM, Kolker A, Engle M, Geboy N, Hendryx M, et al. 2015. Atmospheric particulate matter in proximity to mountaintop coal mines: sources and potential environmental and human health impacts. *Environ. Geochem. Health* 37:529–44
87. Kurth LM, McCawley MA, Hendryx M, Lusk S. 2014. Atmospheric particulate matter size distribution and concentration in West Virginia coal mining and non-mining areas. *J. Exp. Sci. Environ. Epidemiol.* 24:405–11
88. Kuvlesky WP Jr., Brennan LA, Morrison ML, Boydston KK, Ballard BM, Bryant FC. 2007. Wind energy development and wildlife conservation: challenges and opportunities. *J. Wildl. Manag.* 71:2487–98
89. Laden F, Neas LM, Dockery DW, Schwartz J. 2000. Association of fine particulate matter from different sources with daily mortality in six U.S. cities. *Environ. Health Perspect.* 108:941–47
90. Lan Q, Chapman RS, Schreinemachers DM, Tian L, He X. 2002. Household stove improvement and risk of lung cancer in Xuanwei, China. *J. Natl. Cancer Inst.* 94:826–35
91. Lan Q, He X, Shen M, Tian L, Liu LZ, et al. 2008. Variation in lung cancer risk by smoky coal subtype in Xuanwei, China. *Int. J. Cancer* 123:2164–69
92. Lancet Respir. Med. 2015. Obama's Clean Power Plan: a breath of fresh air. *Lancet Respir. Med.* 3:661
93. Laumbach RJ, Kipen HM. 2012. Respiratory health effects of air pollution: update on biomass smoke and traffic pollution. *J. Allergy Clin. Immunol.* 129:3–11; quiz 12–13
94. Lewis J, Hoover J, MacKenzie D. 2017. Mining and environmental health disparities in Native American communities. *Curr. Environ. Health Rep.* 4:130–41
95. Liao Y, Wang J, Wu J, Driskell L, Wang W, et al. 2010. Spatial analysis of neural tube defects in a rural coal mining area. *Int. J. Environ. Health Res.* 20:439–50
96. Lindberg TT, Bernhardt ES, Bier R, Helton AM, Merola RB, et al. 2011. Cumulative impacts of mountaintop mining on an Appalachian watershed. *PNAS* 108:20929–34
97. Liu Q, Lei Q, Xu H, Yuan J. 2018. China's energy revolution into 2030. *Resour. Conserv. Recycl.* 128:78–89
98. Luanpitpong S, Chen M, Knuckles T, Wen S, Luo J, et al. 2014. Appalachian mountaintop mining particulate matter induces neoplastic transformation of human bronchial epithelial cells and promotes tumor formation. *Environ. Sci. Technol.* 48:12912–19

99. Markandya A, Wilkinson P. 2007. Electricity generation and health. *Lancet* 370:979–90
100. Massetti E, Brown MA, Lapsa M, Sharma I, Bradbury J, et al. 2017. *Environmental quality and the US power sector: air quality, water quality, land use and environmental justice*. Rep. ORNL/SPR-2016/772, Oak Ridge Natl. Lab., US Dep. Energy, Oak Ridge, TN
101. McKenzie LM, Allshouse WB, Byers TE, Bedrick EJ, Serdar B, Adgate JL. 2017. Childhood hematologic cancer and residential proximity to oil and gas development. *PLOS ONE* 12:e0170423
102. Mishra SK. 2015. Putting the value to human health in coal mining region of India. *J. Health Manag.* 17:339–55
103. Mishra UC. 2004. Environmental impact of coal industry and thermal power plants in India. *J. Environ. Radioact.* 72:35–40
104. Morgan S. 2018. Spain to nix nuclear and coal power by 2030. *Euractiv*, Nov. 15. **https://www.euractiv.com/section/energy/news/spain-to-nix-nuclear-and-coal-power-by-2030/**
105. Mumford JL, He XZ, Chapman RS, Cao SR, Harris DB, et al. 1987. Lung cancer and indoor air pollution in Xuan Wei, China. *Science* 235:217–20
106. Munawer ME. 2018. Human health and environmental impacts of coal combustion and post-combustion wasters. *J. Sustain. Min.* 17:87–96
107. NaturalGas.org. 2013. Background. *NaturalGas.org*, Sept. 20. **http://naturalgas.org/overview/background/**
108. Nichols CE, Shepherd DL, Knuckles TL, Thapa D, Stricker JC, et al. 2015. Cardiac and mitochondrial dysfunction following acute pulmonary exposure to mountaintop removal mining particulate matter. *Am. J. Physiol. Heart Circ. Physiol.* 309:H2017–30
109. OHSA (Occup. Saf. Health Adm.), US Dep. Labor. 2019. Silica, crystalline. *Health Effects*. **https://www.osha.gov/dsg/topics/silicacrystalline/health_effects_silica.html**
110. Orem W, Tatu C, Crosby L, Varonka MS, Bates A, et al. 2012. *Water chemistry in areas with surface mining of coal*. Presented at Geological Society of America Annual Meeting and Exposition, Charlotte, NC
111. Ostro B, Tobias A, Querol X, Alastuey A, Amato F, et al. 2011. The effects of particulate matter sources on daily mortality: a case-crossover study of Barcelona, Spain. *Environ. Health Perspect.* 119:1781–87
112. Palmer MA, Bernhardt ES, Schlesinger WH, Eshleman KN, Foufoula-Georgiou E, et al. 2010. Mountaintop mining consequences. *Science* 327:148–49
113. Pericak AA, Thomas CJ, Kroodsma DA, Wasson MF, Ross MRV, et al. 2018. Mapping the yearly extent of surface coal mining in Central Appalachia using Landsat and Google Earth Engine. *PLOS ONE* 13:e0197758
114. Pless-Mulloli T, Howel D, King A, Stone I, Merefield J, et al. 2000. Living near opencast coal mining sites and children's respiratory health. *Occupat. Environ. Med.* 57:145–51
115. PSR (Phys. Soc. Responsib.). 2019. *Coal ash: hazardous to human health*. Brief, Phys. Soc. Responsib., Washington, DC. **https://www.psr.org/wp-content/uploads/2018/05/coal-ash-hazardous-to-human-health.pdf**
116. Qi Y, Lu J. 2018. Has China hit peak coal? *Brink: The Edge of Risk*, March 18. **https://www.brinknews.com/has-china-hit-peak-coal/**
117. Qi Y, Stern N, Wu T, Lu J, Green F. 2016. China's post-coal growth. *Nat. Geosci.* 9:564–66
118. Rasmussen SG, Ogburn EL, McCormack M, Casey JA, Bandeen-Roche K, et al. 2016. Association between unconventional natural gas development in the Marcellus Shale and asthma exacerbations. *JAMA Intern. Med.* 176:1334–43
119. Rice KM, Walker EM Jr., Wu M, Gillette C, Blough ER. 2014. Environmental mercury and its toxic effects. *J. Prev. Med. Public Health* 47:74–83
120. Ruhl L, Vengosh A, Dwyer GS, Hsu-Kim H, Deonarine A, et al. 2009. Survey of the potential environmental and health impacts in the immediate aftermath of the coal ash spill in Kingston, Tennessee. *Environ. Sci. Technol.* 43:6326–33
121. Santos MD, Flores Soares MC, Martins Baisch PR, Muccillo Baisch AL, Rodrigues da Silva Junior FM. 2018. Biomonitoring of trace elements in urine samples of children from a coal-mining region. *Chemosphere* 197:622–26

122. Schweinfurth SP. 2013. *Coal—a complex natural resource*. Circ. 1143, US Dep. Inter. US Geol. Survey, Reston, VA. **https://pubs.usgs.gov/circ/c1143/c1143.pdf**
123. Sears CG, Zierold KM. 2017. Health of children living near coal ash. *Glob. Pediatr. Health* 4:2333794X17720330
124. Sellers S, Ebi KL, Hess J. 2019. Climate change, human health, and social stability: addressing interlinkages. *Environ. Health Perspect.* 127:45002
125. Seow WJ, Hu W, Vermeulen R, Hosgood HD III, Downward GS, et al. 2014. Household air pollution and lung cancer in China: a review of studies in Xuanwei. *Chin. J. Cancer* 33:471–75
126. Shearer C, Fofrich R, Davis SJ. 2017. Future CO_2 emissions and electricity generation from proposed coal-fired power plants in India. *Earth's Futur*. 5:408–16
127. Shen M, Chapman RS, Vermeulen R, Tian L, Zheng T, et al. 2009. Coal use, stove improvement, and adult pneumonia mortality in Xuanwei, China: a retrospective cohort study. *Environ. Health Perspect.* 117:261–66
128. Sigsgaard T, Forsberg B, Annesi-Maesano I, Blomberg A, Bølling A, et al. 2015. Health impacts of anthropogenic biomass burning in the developed world. *Eur. Respir. J.* 46:1577–88
129. Smith KR, Frumkin H, Balakrishnan K, Butler CD, Chafe ZA, et al. 2013. Energy and human health. *Annu. Rev. Public Health* 34:159–88
130. Sovacool BK. 2012. The avian and wildlife costs of fossil fuels and nuclear power. *J. Integr. Environ. Sci.* 9:255–78
131. Stout BM, Papillo J. 2004. *Well water quality in the vicinity of a coal slurry impoundment near Williamson, West Virginia*. Rep., Wheeling Jesuit Univ., Wheeling, WV
132. Temple JMF, Sykes AM. 1992. Asthma and open cast mining. *BMJ* 305:396–97
133. Thurston GD, Burnett RT, Turner MC, Shi Y, Krewski D, et al. 2016. Ischemic heart disease mortality and long-term exposure to source-related components of U.S. fine particle air pollution. *Environ. Health Perspect.* 124:785–94
134. Turney D, Fthenakis V. 2011. Environmental impacts from the installation and operation of large-scale solar power plants. *Renew. Sustain. Energy Rev.* 15:3261–70
135. UN. 2015. *China submits its Climate Action Plan ahead of 2015 Paris Agreement*. UN Clim. Change Press Release, June 30. **https://unfccc.int/news/china-submits-its-climate-action-plan-ahead-of-2015-paris-agreement**
136. UN. 2017. More than 20 countries launch global alliance to phase out coal. *United Nations Climate Change*, Nov. 17. **https://unfccc.int/news/more-than-20-countries-launch-global-alliance-to-phase-out-coal**
137. UN. 2018. *2018 revision of world urbanization prospects*. Rep., UN Dep. Econ. Soc. Aff., New York. **https://www.un.org/development/desa/publications/2018-revision-of-world-urbanization-prospects.html**
138. UN. 2018. *The Paris Agreement*. Agreem., UN Framew. Conv. Clim. Change, Bonn, Ger. **https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement**
139. UN. 2018. *World population prospects. The 2017 revision. Key findings and advance tables.* Rep., UN, New York. **https://population.un.org/wpp/Publications/Files/WPP2017_KeyFindings.pdf**
140. US EPA (Environ. Prot. Agency). 2018. *Comparison of ACE and CPP*. Fact Sheet, US EPA, Washington, DC. **https://www.epa.gov/sites/production/files/2018-08/documents/ace-cpp_side_by_side.pdf**
141. US EPA (Environ. Prot. Agency). 2018. Surface coal mining in Appalachia. *US Environmental Protection Agency*. **https://www.epa.gov/sc-mining**
142. US EPA (Environ. Prot. Agency). 2019. *EPA finalizes Affordable Clean Energy Rule, ensuring reliable, diversified energy resources while protecting our environment*. News Release, June 19. **https://www.epa.gov/newsreleases/epa-finalizes-affordable-clean-energy-rule-ensuring-reliable-diversified-energy**
143. Walker Whitworth K, Kaye Marshall A, Symanski E. 2018. Drilling and production activity related to unconventional gas development and severity of preterm birth. *Environ. Health Perspect.* 126:037006
144. Watts N, Amann M, Arnell N, Ayeb-Karlsson S, Belesova K, et al. 2018. The 2018 report of the *Lancet* Countdown on health and climate change: shaping the health of nations for centuries to come. *Lancet* 392:2479–514

145. Wei H, Feng Y, Liang F, Cheng W, Wu X, et al. 2017. Role of oxidative stress and DNA hydroxymethylation in the neurotoxicity of fine particulate matter. *Toxicology* 380:94–103
146. Werner AK, Vink S, Watt K, Jagals P. 2015. Environmental health impacts of unconventional natural gas development: a review of the current strength of evidence. *Sci. Total Environ.* 505:1127–41
147. Yapici G, Can G, Kiziler AR, Aydemir B, Timur IH, Kaypmaz A. 2006. Lead and cadmium exposure in children living around a coal-mining area in Yatağan, Turkey. *Toxicol. Ind. Health* 22:357–62
148. Zierold KM, Sears CG. 2015. Community views about the health and exposure of children living near a coal ash storage site. *J. Community Health* 40:357–63
149. Zocche JJ, Damiani AP, Hainzenreder G, Mendonça RA, Peres PB, et al. 2013. Assessment of heavy metal content and DNA damage in *Hypsiboas faber* (anuran amphibian) in coal open-casting mine. *Environ. Toxicol. Pharmacol.* 36:194–201
150. Zullig KJ, Hendryx M. 2011. Health-related quality of life among central Appalachian residents in mountaintop mining counties. *Am. J. Public Health* 101:848–53