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Trace Metal Content of Coal Exacerbates Air-Pollution-Related Health Risks: The Case of Lignite Coal in Kosovo

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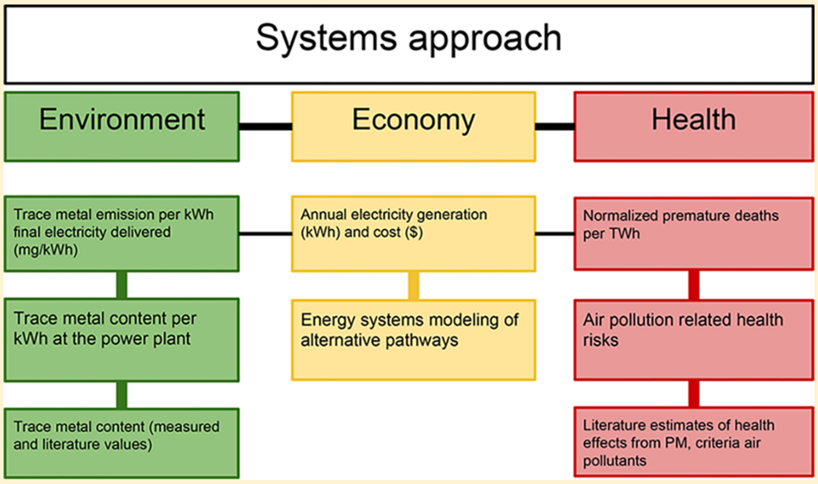
Supporting Information



ABSTRACT: More than 6600 coal-fired power plants serve an estimated five billion people globally and contribute 46% of annual CO_2 emissions. Gases and particulate matter from coal combustion are harmful to humans and often contain toxic trace metals. The decades-old Kosovo power stations, Europe's largest point source of air pollution, generate 98% of Kosovo's electricity and are due for replacement. Kosovo will rely on investment from external donors to replace these plants. Here, we examine non-CO_2 emissions and health impacts by using inductively coupled plasma mass spectrometry (ICP-MS) to analyze trace metal content in lignite coal from Obilic, Kosovo. We find significant trace metal content normalized per kWh of final electricity delivered (As (22.3 ± 1.7), Cr (44.1 ± 3.5), Hg (0.08 ± 0.010), and Ni (19.7 ± 1.7) mg/kWh$_e$). These metals pose health hazards that persist even with improved grid efficiency. We explore the air-pollution-related risk associated with several alternative energy development pathways. Our analysis estimates that Kosovo could avoid 2300 premature deaths by 2030 with investments in energy efficiency and solar PV backed up by natural gas. Energy policy decisions should account for all associated health risks, as should multilateral development banks before guaranteeing loans on new electricity projects.

1. INTRODUCTION

There is increasing global debate on the sustainability of coal as a source of electricity.[1−3] In Europe and the United States, low-cost renewable energy options such as solar and wind, along with the natural gas revolution, have led to a rapid closure of coal plants. In other regions, however, coal is experiencing a renaissance,[4] with increasing proposals for new plants across South and Southeast Asia. In South East Europe, coal use remains contentious because of (1) the role of multilateral development bank finance, (2) rising concerns over air quality, and (3) planning for potential future European Union integration.[5,6] The use of locally abundant lignite coal in subcritical coal plants without substantial pollution control technologies violates the EU Industrial Emissions Directive and could jeopardize admission to the European Union.[7] Coal is becoming increasingly difficult to justify on an economic basis.

Coal has been the dominant energy source around the world since the industrial revolution and is responsible for a significant proportion of greenhouse gas emissions and air-pollution-related deaths worldwide. In total, coal currently contributes 46% of annual global CO_2 emissions.[4,8] Associated

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fine particulate matter (PM) emissions and toxic air contaminants contribute significantly to the burden of disease from air pollution.[9] However, the majority of health-effects studies focus on the magnitude of PM emissions and have not applied source-specific information to risk calculations.[10−12] Even in countries where emissions accounting is relatively transparent, trace metal emissions remain unaccounted for in PM indices despite their established presence in geologic coal analysis.[13] Investment decision frameworks rarely consider emerging research that implicates hazardous air pollution and PM emissions in the global burden of disease.

Kosovo, a country on the verge of implementing a suite of new supply- and demand-side electricity investments, currently relies on lignite coal for more than 98% of its electricity generation. Although lignite has the lowest quality and calorific value of all coal types, its local abundance explains its continued use. The World Bank has proposed financing a new lignite coal-based power plant to replace the scheduled decommissioning of the 1962 era lignite-based "Kosovo A" facility and to address the security of Kosovo's electricity supply. The plan would continue to use lignite coal as a fuel source and improve efficiency with newly available technology. This is proposed as a means to improve electricity reliability and air quality, as power plant efficiency gains could marginally reduce air pollution.

While all coal produces hazardous emissions when combusted, impurities in lignite coal present significantly greater threats to human health and the environment compared with other coals.[11] However, little information is publically available regarding the trace metal content of Kosovo's lignite supply and its associated public health impacts. Research into the composition of lignite coal, both globally and specifically in Kosovo, could inform more comprehensive evaluations of the environmental and health impacts of fossil-fuel-based electricity generation.[14] It could also identify opportunities to reduce illness and premature deaths by switching to alternative sources of electricity.

Due to the widespread use of coal for electricity production, scientists still need more geographically specific information on trace metal content. Here, we investigate the chemical composition of lignite coal from Obilic, Kosovo (the main lignite coal mine located 12 km outside of the capital city, Pristina, and the primary coal source in Kosovo). Using inductively coupled plasma mass spectrometry (ICP-MS), we characterize the identity and content of hazardous trace metals in coal. We propose a new metric of trace metal content per final unit of electricity delivered. Aerosolized arsenic, nickel, and other trace metals in particulate matter are typically difficult to quantify, especially in regions that lack significant air monitoring and sensing equipment. These heavy metals are also present in fly ash. Our metric enables scientists and investors to understand the geographic differences in coal content, which may alter the emissions profile projected for new energy projects.

Coal studies have typically analyzed the chemical composition of higher density bituminous and anthracite coals, demonstrating the presence of hazardous metals. Arsenic, cadmium, chromium, mercury, nickel, selenium, and lead have been detected in bituminous coal samples from the United States and Brazil.[15,16] By contrast, few studies investigate the chemical composition and emissions from lignite coal. Despite lignite coal's relatively low energy density, local availability leads many countries to depend on lignite, including those in South East Europe. Countries in Southeast Asia, including Vietnam and Indonesia, plan to increase combustion of lignite coal for electricity generation.[12,17,18] Continued investment in lignite by multinational finance organizations influences global patterns of energy production and consumption, yet they so far fail to consider geographic differences in the chemical composition of coal or account for its public health impact. Global estimates suggest coal combustion is responsible for 2−5% of total anthropogenic arsenic emissions.[19] In the United States, coal-fired power plants contribute approximately 62% of arsenic, 50% of mercury, 28% of nickel, and 22% of chromium emissions.[20] These toxic heavy metals harm the environment and human health. Although previous studies have identified externalized costs of burning coal for electricity generation, there are relatively few data points on the impact on human health of trace metals released through combustion.[11,12,21,22]

We investigate the trace metal content (arsenic, mercury, chromium, and nickel) in Kosovo lignite coal. We present this information alongside estimates of annual PM emissions. Because trace metal content is not currently accounted for in estimates of premature death attributable to air pollution, these estimates likely undercount the actual health toll of coal combustion. Therefore, our analysis could inform further research.

2. HUMAN HEALTH IMPACTS OF TRACE METALS

Power plants remain one of the largest sources of toxic air emissions, including metals.[11,23,24] People can be exposed to trace metals in particulate matter through inhalation, ingestion, and dermal contact. Recent studies highlight the disproportionate impacts of toxic air pollution on low-income children, linking cumulative exposures to toxic air pollutants with adverse effects on the developing fetus including preterm births, low birth weight, cognitive and behavioral disorders, asthma, and respiratory illness.[25] For example, once arsenic enters the environment, it cannot be destroyed, so any effects will persist until the arsenic becomes chemically isolated from the biosphere. Arsenic is a known human carcinogen, irrespective of exposure route, and is particularly linked to lung cancer.[26] Arsenic can also cause several skin disorders and can reduce immune function by decreasing cytokine production.[27] Toxic heavy metals have long residence times and tend to bioaccumulate in the human body. For example, it may take a few days for a single, low dose of arsenic to be excreted, and mercury has an estimated half-life in the human body of around 44 days.[28,29] Continuous or daily exposure in the context of relatively slow elimination translates into steadily increasing tissue concentrations of these toxic metals.

In adults, chronic mercury exposure can produce tremors, cognitive dysfunction, and other nervous system dysfunction. However, the most harmful effects of mercury exposure occur in the developing fetus. Even at low concentrations, prenatal mercury exposure can decrease IQ and cause long-term cognitive impairment, depending on timing and extent of exposure.[30] Prolonged inhalation of mercury vapor in adults can lead to pneumonia, corrosive bronchitis, and tremors. Increasingly, governments around the world have incorporated mercury emissions into standards for reducing emissions of toxic air contaminants, as power plants serve as the dominant source of mercury in air pollution. Despite this trend and proven pollution control technologies to limit mercury emissions, relatively few governing bodies set standards or limit mercury from power plants.[31]

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Table 1. Trace Metals Present in Lignite Coals and Their Associated Environmental and Health Impacts

Heavy metal (CAS no.)[32]	Arsenic (7440-38-2)	Chromium metal, Chromium(II), Chromium(III), Chromium(VI) (7440-47-3)	Mercury (7439-97-6)	Nickel (7440-02-0)
Environmental Impact	Contaminates groundwater, disrupts plant growth and development, and decreases crop yields	Increases uric acid concentration in birds' blood and alters animal growth	Impairs nervous system and other organ systems in animals	Causes genetic alterations in fish and possible death and toxic to development organisms
Human Health Impact	Impairs immune system and increasing susceptibility to lung cancer	Causes reproductive and developmental harm and increases risk of certain cancers	Causes cognitive impairment in children and overstimulates central nervous system	Increases risk of lung cancer and causes nickel dermatitis
Boiling Point (°C)	465	2482	357	2730
Solubility in water (g/L)	20 (arsenic trioxide) at 20 °C	1680 (chromium trioxide) at 25 °C	74 (Mercury II chloride) at 25 °C	553 (nickel chloride) at 20 °C

Coal combustion is one of the major anthropogenic sources of chromium air pollution.[23] Chromium(VI) is the most hazardous valence state; hexavalent chromium is a known carcinogen and causes both developmental and reproductive toxicity. Some occupational studies attribute decreased sperm count and quality to chromium(VI) in exposed workers.[32] Furthermore, chromium can have synergistic effects with other organic carcinogens, and mixed exposures can increase the risk of certain cancers.

One of the most common forms of allergic dermatitis is nickel dermatitis caused by exposure to nickel-containing compounds. Additionally, inhalation of high levels of nickel increases the risk of lung and nasal cancer.[33]

Table 1 summarizes environmental and human health impacts from trace metals found in lignite coal samples. It also describes solubility in water and boiling point for arsenic (III or V), chromium (0, II, III, and VI), mercury(II), and nickel(II). Solubility and boiling point are important to determine whether the metals will undergo phase changes during power plant combustion. The boiling point of arsenic trioxide is approximately 465 °C, which is within the range of a standard boiler in a coal plant, leading to volatilization of arsenic, which could aerosolize within particulate matter.

3. METHODS

Analysis of Trace Metal Content Per Final Unit of Electricity Delivered. We obtained 50 g samples of Pliocene lignite coal found in the Kosovo basin located at the main coal mine in Obilic, Kosovo (within a 5 km radius of 42.689° N, 21.069° E, Figure S1). Trace metals analysis by ICP-MS was conducted by the Curtis & Tompkins Laboratory (Berkeley, CA) according to Environmental Protection Agency (EPA) standard procedures appropriate for each metal. Sample preparation was performed by EPA method no. 3052, and then EPA method no. 6020 was used for the detection of for aluminum, arsenic, beryllium, cadmium, chromium, copper, lead, nickel selenium, silver, thallium, and zinc and EPA method no. 7471A for mercury (see the Supporting Information).[34−36]

Using the measured trace metal content in lignite samples, we estimate the trace metal emissions by creating an "emissions factor". The emissions factor is defined as the mass of trace metals (in milligrams) emitted from coal combustion per kWh of final electricity delivered (see eq 1 in the Supporting Information). To do this, we developed an open-source spreadsheet model to evaluate the trace metal content per kWh of final electricity delivered at different transmission, distribution, power plant efficiencies, and heat rates. We input ICP-MS results of trace metal content and known calorific values (kJ/kg) of different coal types into the model. The model parameters include generation, transmission, and distribution system efficiency of electricity (n_t and n_d), calorific value of coal (kJ/kg), and efficiency and heat rate of the coal-fired power plant. We use literature-cited data for international global average trace metal content and literature values for Chinese coals.[37−39] The model calculates a unit conversion from measured trace metal content (mg/kg) into trace metals per unit electricity (mg/kWh$_e$) based on plant characteristics such as heat rate and efficiency. This metric enables fair comparisons of the potential impacts of trace metal emissions across different countries' coal generation, transmission, and distribution systems by accounting for the relative energy densities of different coal types and the efficiencies of different plants and electric transmission and distribution systems.

We also use the spreadsheet model to compare the trace metal content in Kosovo coal to the reported mean trace metal content (and standard deviation values) from global data sets. Although it is not a spatially explicit chemical fate and transport model, it provides a reasonable range estimate of the release of trace metals at the smokestack while taking into consideration the local generation, transmission, and distribution system conditions that may increase emissions intensity.

During coal combustion, trace metals are distributed among flue gas, bottom ash, and fly ash. We use trace metal mass balances and estimate that 1−10% of As, Cr, and Ni will appear in flue gas, based on estimates in the literature. Mercury is evaluated separately because it is more volatile, with 80% of mercury appearing in flue gas.[40,41] The general model for estimating trace metal content per final unit of electricity delivered and trace metal partitioning is detailed in the Supporting Information.

We report mean, standard deviation, and lower-upper bound ranges for milligrams of trace metals per kilowatt hours of final electricity delivered. After estimating the emissions factor for each individual trace metal, we can also estimate system-wide emissions from electricity generation:

$$E = \sum_{k} \sum_{m} A_{i,k} * EF_{i,k,m} \tag{1}$$

where E is emissions, k is the fuel type, m is the emissions control devices, and i is the power plant. This framework investigates the potential to reduce environmental health impacts by improving power plant and grid efficiency.

Estimation of Air-Pollution-Related Health Risk. In addition to estimating trace metal content per final kilowatt hour of electricity delivered (the emissions factor), in a separate analysis we use an energy systems model that evaluates the cost of possible future electricity scenarios to estimate air-pollution-related health risk attributable to the air pollutants associated

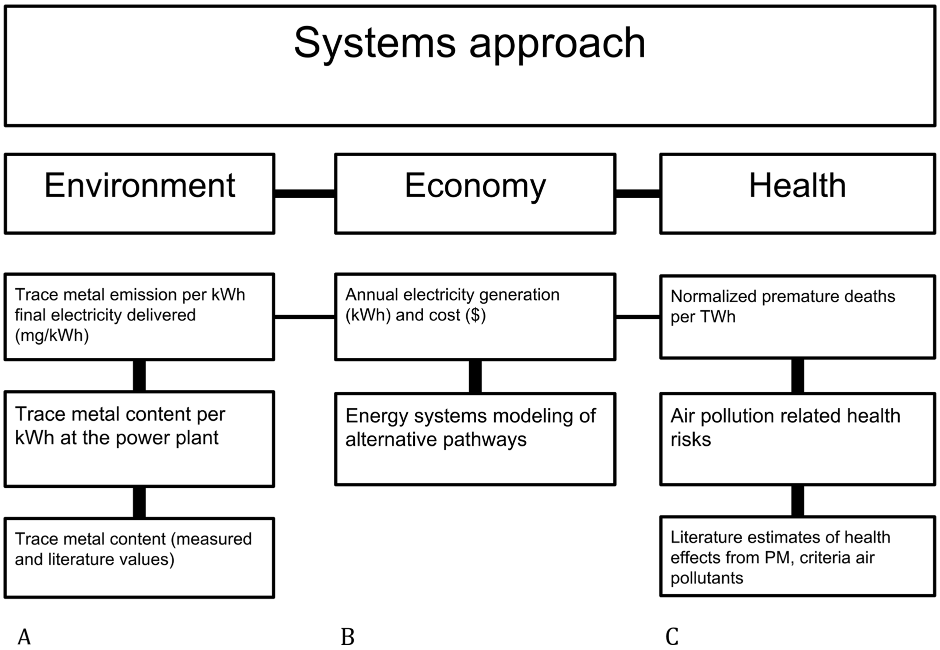

Figure 1. Overall approach of the three parallel analyses that evaluate environmental (A), economic (B), and health (C) impacts of lignite coal in Kosovo.

Table 2. ICP-MS Heavy Metal Content in Kosovo Lignite Compared to Lignite from Other Regions[a]

			Content in coals from China[38,39]		Content in coals from the United States[37]		
Heavy Metal	Content in Kosovo lignite coal	International Energy Agency global average	Bai et al. (2007)	Dai et al. (2012)	Arithmetic mean	Geometric mean	Content in coals around the world[37]
Arsenic	9.6 ± 1.6	2.69	4.09	3.79	24	6.5	8.3
Chromium	19 ± 1.7	17.6	16.94	15.4	15	10	16
Mercury	0.035 ± 0.020	0.091	0.154	0.163	0.17	0.10	0.10
Nickel	8.5 ± 1.7	11.1	14.44	13.7	14	9	13

[a] All values are in mg metal/kg coal.

with each scenario. This provides context for systems scale risk analysis. We can also use the energy systems model to estimate systems-level trace metal content that could be released into the environment in each scenario of future energy sources. Figure 1 shows the overall approach and how these analyses are conducted independently and used to support each other.

To analyze the air-pollution-related health risk from a variety of future electricity portfolios, we use four representative annual electricity generation scenarios developed by a stakeholder analysis in consultation with civil society and lending partners. Following the model established in Kittner et al. (2016), we compare the associated environmental and public health risks (from air pollution and trace metals) for each scenario.[17] We investigate a corresponding business-as-usual case, evaluating the net costs of: (1) constructing a new lignite plant, (2) using energy efficiency measures to meet Euro2030 targets, (3) transitioning to low-cost solar without natural gas backup, and (4) using solar augmented by natural gas for system flexibility. For a full detailed evaluation of the spreadsheet model, the associated paper describes the model and assumptions used for analyzing Kosovo's power sector.[17] For scenarios that include natural gas, solar, and wind, we use the same values for health and environmental impacts of these technologies as reported in the literature for continental Europe.[42]

The annual electricity generation portfolio values (kWh) are then applied to an occupational and air-pollution-related risk methodology called ExternE: Externalities of Energy.[42,43] The ExternE model predicts health impacts attributable to air pollution and occupational risks for each energy technology scenario expressed per kWh. The ExternE model accounts for reduction in life expectancy and cancers, e.g., premature death. The premature death end point estimates excess mortality attributable to exposure to $PM_{2.5}$, sulfur dioxides, nitrogen oxides, and ozone.

4. RESULTS

We present the results in two parts. First, we report the trace metal content analysis represented in Figure 1A, and we report the results from Kosovo alongside trace metal content of lignite coal in China and globally (based on IEA data) to put the numbers into perspective. Second, we use energy systems modeling represented by Figure 1B as inputs to show premature deaths represented by Figure 1C. Finally, we discuss the results. Table 2 contains the results of ICP-MS trace metal analysis for lignite coal in Kosovo compared with (1) average trace metal content in a cross-section of lignite coal globally (IEA) and (2) trace metal content reported in the literature for lignite coal in the United States and China.[37−39]

Figure 2 reports the trace metal content per final unit of electricity delivered in kilowatt hours (reported in mg/kWh). This only includes metal content in the flue gas. We simulate

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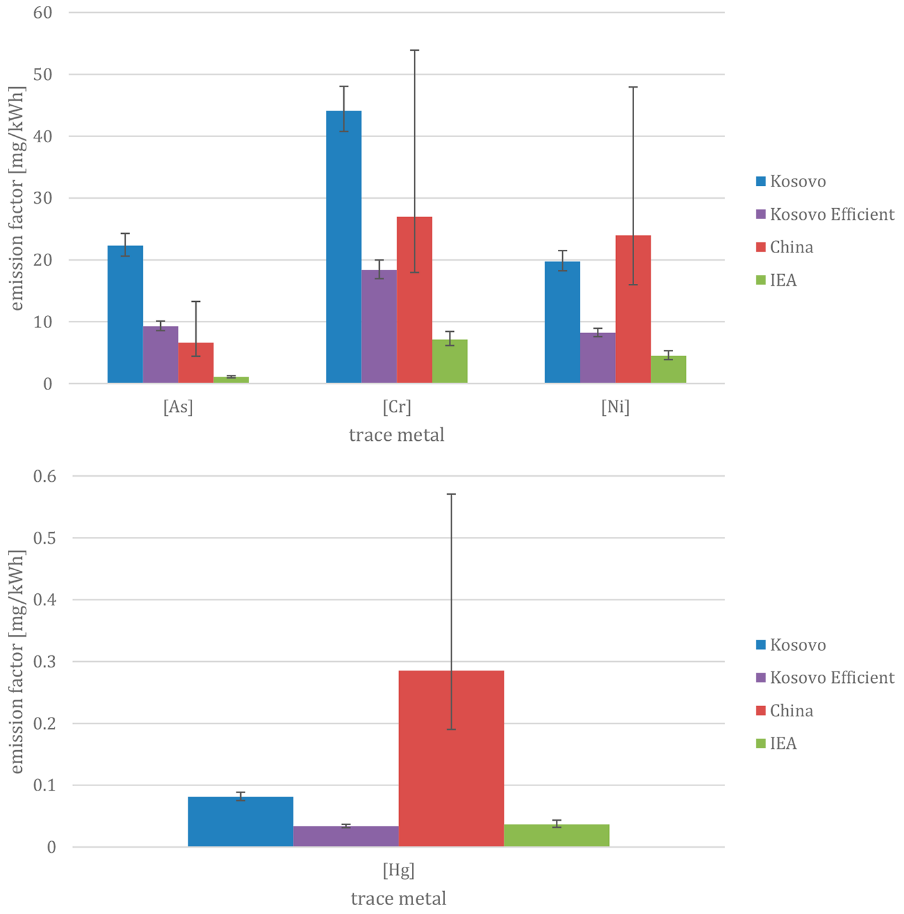

Figure 2. Trace metal emissions for [As], [Cr], [Ni], [Hg], expressed per kilowatt hour of final electricity delivered by country. Variation in China is likely due to significant diversity in reported mercury content in lignite that spans multiple geologic basins.[39]

the existing Kosovar grid with 30% transmission and distribution losses (represented by "Kosovo") and compare it to an improvement to only 10% losses, which represents an upper bound for typical transmission and distribution efficiency ("Kosovo Efficient" in Figure 2). Additionally, we estimate the normalized trace metal content per unit of electricity delivered in China and globally (IEA estimate) for lignite coals with transmission and distribution efficiency of 10% to account for line losses, derating, and congestion.[44] These are reasonable upper bound estimates based on EIA transmission and distribution losses data.[45,46] We find that even if Kosovo significantly improves transmission and distribution systems, the poor quality of the lignite coal means that trace metals emissions will still be significantly higher than they would be for a coal source on par with the IEA average metal content in global lignite.

We find high arsenic and chromium content compared with IEA average values for lignite in the ICP-MS analysis. The mercury (0.08 mg/kWh [Hg]) and nickel (19.7 mg/kWh [Ni]) content, while lower than the Chinese average values for lignite (0.28 mg/kWh [Hg] and 24 mg/kWh [Ni]), may pose public health concerns to the nearby Kosovo community. This raises concerns for fly ash management and also aerosolization of trace metals with particulate matter emissions.

5. ACCOUNTING FOR HEALTH

Table 3 highlights the deaths from air-pollution-related risk calculated for different energy technologies following the ExternE method detailed by Markandya and Wilkinson.[42] The model assumes a population density of 160 people/km^2, based on Kosovo. The model characterizes pollutants of different electricity technologies based on inputs of annual electricity generation (total kWh), and it only considers health impacts for coal and natural gas (based on emission of PM_{10}, $PM_{2.5}$, SO_x, NO_x, and O_3). It does not include source-specific trace metals in the PM burden, similar to the current version of USEtox.[9,47] One limitation in the ExternE model is the assumption of a linear relationship between $PM_{2.5}$ exposure and premature death. Research in the past decade suggests that at low background concentrations of $PM_{2.5}$, the concentration−response relationship is supralinear.[48] However, in this case, a linear relationship is the best estimate given that (1) background PM levels are high enough to appear in the linear portion of the concentration−response curve, (2) there is limited empirical data available to use more sophisticated models, and (3) our knowledge of local geography that concentrates pollution in a valley in Kosovo. An alternative approach could use TRACI, a model developed by the EPA.[49−51] However, TRACI is not explicitly set up for power plants, as was ExternE, and it is generic (using nonspeciated metals) for metal species. TRACI is also intended for the United States. In this instance, relying on TRACI would compound the uncertainties of this model. Future updates to USEtox and TRACI would allow for research on the specific health impact of trace metal species in the PM burden, but the current versions have not yet accounted for speciated

Table 3. Air-Pollution-Attributable Morbidity and Mortality in Four Energy Scenarios Evaluated in Kosovo's Power Sector Projected for 2016−2030

	Air-pollution-related risk		
Scenario	Deaths	Serious illness	Minor illness
Business-as-usual	3200 (800−12 700)	29 000 (7300−88 000)	1 700 000 (430 000−6 900 000)
Euro2030	2000 (510−8100)	18 500 (4600−75 000)	1 100 000 (280 000−4 400 000)
Solar without natural gas	1300 (320−5200)	12 000 (2900−47 000)	700 000 (180 000−2 800 000)
Solar with natural gas	900 (230−3600)	8400 (2100−33 700)	460 000 (120 000−1 800 000)

composition of trace metals in the PM burden.[47] Table S5 details existing annual air pollutant emissions.

The death rates are expressed as mean estimates with 95% confidence intervals. While the model includes acute and chronic health effects, chronic health effects account for between 88 and 99% of the total impact. Serious illness (acute and chronic) includes cerebrovascular events, congestive heart failure, and chronic bronchitis. Minor illness includes restricted activity days, bronchodilator use, persistent cough, and lower-respiratory symptom days for those with asthma. We adapt the model to the Kosovo case using scenarios from Kittner et al. (2016), and we aggregate excess risk of deaths over the projected period from 2016 to 2030.[17] Full annual electricity generation mix until 2030 of the scenarios analyzed is detailed in Figures S2−5. Additionally, the Euro2030, solar without natural gas, and solar with natural gas cases each cost less than the business-as-usual scenario by €200−400 million euros before considering health and environmental externalities. The population of Kosovo is only 1.8 million, and this model shows 1.7 million cases of minor illnesses in the business-as-usual case. Business-as-usual coal includes the use of the best available pollution control technologies.

6. DISCUSSION

The scenarios depicted demonstrate that there is a range of future cost-competitive paths for the electricity sector in Kosovo. Kittner et al. (2016) finds the alternative scenarios to coal-based power generation to cost less on a direct levelized cost basis before considering externalities. This study takes the next step to identify and estimate some of the public health risks that better characterize the overall cost of each scenario accounting for all externalities. Interestingly, natural gas, which produces less PM pollution, may provide public health benefits compared to lignite coal, although it could have the consequence of delaying substantial reductions in CH_4 or CO_2 emissions. In the other scenarios, low-cost solar and energy efficiency alone would mitigate air pollution related-risk, though not to the same extent as the scenario that combines these two interventions with natural gas. The scenarios without natural gas rely on continued operation of the Kosovo B coal-fired power plant for base-load power generation. Emerging low-cost energy storage technologies or increased regional power trade could change this result in ways that are not detailed in this analysis.[51] They could also reduce the use of coal in the energy efficiency and renewable scenarios that do not employ natural gas. One clear outcome remains: sustained use of lignite coal poses serious air-pollution-related health risk and an introduction of natural gas and renewables to provide flexibility in Kosovo's grid could meet future electricity needs while providing a cleaner and safer alternative to lignite coal. It is possible to incorporate health risk in addition to cost when comparing electricity development pathways.

At full operating capacity, the Kosovo A and B facilities consume 30 000 tons of lignite coal per day. In 2005, the CO_2 emissions were estimated at 5.7 million tons. SO_x emissions exceeded European Commission standards by 333 $\mu g/m^3$, and PM emissions were exceeded by an order of magnitude (Table S5).[53] These results suggest that coal contributes significantly to air pollution. Air pollution also contributes to premature mortality, and a significant portion of the air pollution in Kosovo is attributable to lignite coal. A replacement of coal infrastructure with natural gas could reduce thousands of air-pollution-related illnesses and deaths in the coming decade. The renewable scenarios may also dramatically reduce CO_2 emissions. The lack of low-NO_x boilers or other pollution control technologies on Kosovo's power plants means that our model likely underestimates the impact of air pollutants that form when power plant emissions undergo chemical oxidation. The scenario in which solar is introduced without gas demonstrates that potential public health benefits of solar power and energy efficiency will be attenuated if coal remains a significant source of base-load power generation. Emerging energy storage technologies could change this result.[52] We project that a full-scale transition away from coal or natural gas would reduce air-pollution-related risk by the largest increment; however, Kosovo B lignite power station is expected to remain in operation through 2030.[52]

There are significant short- and medium-term public health benefits to switching from coal to gas. However, natural gas may raise implementation challenges due to a lack of domestic supply.[17] The flexibility afforded by the addition of natural gas to power system operations could also provide load balancing for intermittent solar and wind in the case that planned regional interconnection projects are delayed or are subject to political turmoil. It may seem counter-intuitive to propose natural gas as a stopgap solution, given the lack of defined climate benefits; however, the cost of continued lignite coal combustion that we estimate in the form of predicted air-pollution-related deaths in Kosovo merits this transition.

Particulate matter, specifically PM_{10} and $PM_{2.5}$, accounts for about 3% of cardiopulmonary and 5% of lung cancer deaths worldwide, and the burden of disease related to similar ambient air pollution may be even higher.[54] Heavy metals, like the ones studied in this paper, could contribute not only individually but also synergistically to the toxicity of particulate matter released from the coal combustion process, although local monitoring of metal content and emissions could help verify our modeled estimates. We suspect ours are underestimates because our tests of Kosovo lignite reveal higher trace metals content than the coals on which most models are based except for mercury. Arsenic in fly ash is a source of groundwater contamination.[55] Nickel, chromium, and mercury can increase the risk of developing certain cancers, especially for vulnerable populations like children and those who already have asthma or chronic obstructive pulmonary disease.

In the short term, a few remedy measures could potentially reduce air-pollution-related risk due to trace metal presence in lignite coal. These include installation of flue gas desulphurization units, electrostatic precipitators, and fabric filters for PM less than 10 μm in size. Additionally, low-NO_x boilers or selective catalytic reduction (SCR units) could reduce NO_x emissions. However, the largest health impact would come from shutting down Kosovo A and transitioning to a more-sustainable power sector that does not include combustion of lignite coal. The cost and availability of low-pollution alternatives including solar photovoltaics, wind, biomass, and small-scale hydropower could meet electricity generation needs while dramatically reducing impacts on public health and the environment.[56]

The trace metals found in precombusted lignite coal in Kosovo are only one aspect of the overall public health threat. Coal-fired power plants release a variety of pollutants (particulate matter, sulfur dioxide, nitrogen oxides, heavy metals and radionuclides) that in this case is likely contribute to thousands of premature deaths in Kosovo over the next decade. Simply increasing efficiency of current energy production and distribution systems is not enough to protect public health because the same coal is still being burned; burning a higher grade coal could reduce chemical emissions slightly but is unlikely to significantly reduce the public health impact of particulate matter emissions. For this reason, stakeholders should prioritize sustainable energy scenarios that reduce dependence on coal. This does not detract from the value of improving energy efficiency on the demand side, or by improving energy transmission and distribution, but it highlights that substantial upgrades in the existing infrastructure should have the goal of reducing health impacts of the electricity supply source. Our research illustrates that the chemical composition of precombusted coal is a critical factor to consider when modeling human and environmental health impacts of electricity generation.

We recommend that multilateral development banks incorporate public health risk analysis into their finance decision-making frameworks to reflect emerging research on the global burden of disease caused by energy production, particularly coal-fired power plants. Most international financial institutions are not required to carry out a public health risk analysis prior to investment. We find that, for example, introducing natural gas for system flexibility could also reduce premature deaths attributable to particulate matter exposure as well as potential health risks from exposure to the toxic metals present in emissions from lignite coal combustion. Finally, we advocate for a reappraisal of financing options for a coal-fired power plant in Kosovo, as renewable electricity options not only are less expensive but also could improve the poor local air quality and reduce air-pollution-related premature deaths.[17]

A better monitoring framework for PM emissions from lignite coals could improve environmental and public health outcomes because the current risk assessment framework does not account for the actual composition of particulate matter. Determining the trace metal content at the same time as $PM_{2.5}$ and PM_{10} concentrations are assessed would more accurately reflect current research on the environmental and human health impacts of toxic metals in air pollution. Because the toxicity of common trace metals is relatively well-characterized, understanding the relationship between the composition of particulate matter and the health hazards posed by toxic air contaminants is a critical topic for future research.[57]

Further research into the composition of lignite coal used for energy production and its unintended impacts on human health could help countries or regional entities conduct integrated resource plans for future energy infrastructure that account for population health. Information on the impact of trace metals in coal could improve decision-making by energy planners, and the international institutions that finance large infrastructure projects. Additionally, such information could help address the challenges of coal-based electricity generation projects identified by justice-based and legal frameworks, such as the need for due process, sustainability, and intra- and intergenerational equity, especially given the historical legacy of Kosovo C.[58]

The arsenic and chromium content we measured in samples from the Kosovar Pliocene basin exceed global IEA averages for lignite. There is cause for concern that these metals, as well as other toxic metals such as the mercury and nickel also found in the lignite coal samples, are not currently accounted for in PM emission risk assessments and could negatively impact public health by increasing the surrounding community's risk for neurodevelopmental impacts, respiratory illness, cancers, cardiovascular disease, neurological impairment and premature death. Our modeling indicates that the continued use of lignite coal is detrimental to public health. We have shown previously (Kittner et al. (2016)) that the costs of the renewable energy options are below those of fossil fuels.[17] With the continuing progression of renewables, the economic case for renewable energy is only getting better while the costs of coal are rising. Coal must be phased out to address the known public health impacts of air pollution. Substituting natural gas for lignite coal electricity could improve public health; however, it may not reduce carbon emissions in a similar manner. Before financing a new coal-fired power plant in Kosovo that burns lignite coal, international financial institutions should account for air-pollution-related public health risk and additional burdens.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.7b04254.

> Figures showing a map of the lignite coal mine, projected sources of energy generation, and materials flow. Equations showing trace metal emissions factor and mass balance. Tables showing ICP-MS analysis, chemical analysis, trace metal emissions, and annual emissions. (PDF)

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