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Air Quality and Health Impact of Future Fossil Fuel Use for Electricity Generation and Transport in Africa

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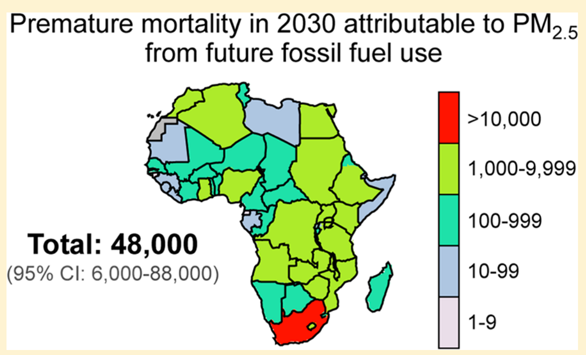
Supporting Information

ABSTRACT: Africa has ambitious plans to address energy deficits and sustain economic growth with fossil fueled power plants. The continent is also experiencing faster population growth than anywhere else in the world that will lead to proliferation of vehicles. Here, we estimate air pollutant emissions in Africa from future (2030) electricity generation and transport. We find that annual emissions of two precursors of fine particles ($PM_{2.5}$) hazardous to health, sulfur dioxide (SO_2) and nitrogen oxides (NO_x), approximately double by 2030 relative to 2012, increasing from 2.5 to 5.5 Tg SO_2 and 1.5 to 2.8 Tg NO_x. We embed these emissions in the GEOS-Chem model nested over the African continent to simulate ambient concentrations of $PM_{2.5}$ and determine the burden of disease (excess deaths) attributable to exposure to future fossil fuel use. We calculate 48000 avoidable deaths in 2030 (95% confidence interval: 6000−88000), mostly in South Africa (10400), Nigeria (7500), and Malawi (2400), with 3-times higher mortality rates from power plants than transport. Sensitivity of the burden of disease to either population growth or air quality varies regionally and suggests that emission mitigation strategies would be most effective in Southern Africa, whereas population growth is the main driver everywhere else.



1. INTRODUCTION

Africa is yet to experience the fossil fueled industrial revolutions of Europe, the US, China, and India that inevitably lead to air quality degradation and deleterious environmental and health effects.[1,2] Many countries in Africa are undergoing the fastest population growth rates (>2% a^{-1}) in the world so that by 2100, the population in Africa could rival that in Asia.[3] Currently the majority of people in Africa rely on biomass (wood, crop residue, charcoal) for energy. Proven coal reserves are low (13 billion tonnes); an order of magnitude less than in the US (251 billion tonnes).[4] There are more proven natural gas reserves in Africa (490 trillion cubic feet or TCF) than in North America (380 TCF),[4] but the infrastructure to utilize this resource has been slow to develop.[5,6] Given this mix of resources and challenges, Africa is in a unique position to leapfrog dependence on fossil fuels and adopt renewable sources like wind and solar that are abundant and cheap.[7] This would address crippling energy deficits, meet its rising energy needs,[8] and reduce exposure to hazardous indoor air pollution from burning biomass.[9] Knowledge of the potential health impacts of exposure to ambient air pollution from fossil fuel combustion would help incentivize this transition.

Exposure to fine particles with aerodynamic diameter <2.5 μm ($PM_{2.5}$) results in deleterious health outcomes.[10] In Africa, $PM_{2.5}$ is dominated by windblown dust from the Sahara and Namib Deserts.[11,12] Other sources include diffuse and very inefficient combustion from intense dry season open fires (biomass burning),[6,13] household burning of charcoal, wood, and crop residue,[14] and open trash burning in the absence of refuse collection services and infrastructure.[15]

Current (2012) premature deaths in Africa attributable to exposure to ambient $PM_{2.5}$ from fossil fuels, mostly for power generation and road transport, is dominated by local sources in South Africa and distant sources in Europe.[16] Combustion of fossil fuels by power plants and vehicles releases large quantities of nitrogen oxides ($NO_x \equiv NO + NO_2$), sulfur

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dioxide (SO_2), and primary particles comprising organic aerosol (OA) and black carbon (BC). Vehicles can also be a large source of nonmethane volatile organic compounds (NMVOCs).[14] NO_x, SO_2, and NMVOCs oxidize to form secondary aerosols (nitrate, sulfate, and secondary organic aerosols or SOA) that contribute to $PM_{2.5}$. Many African countries have plans to use fossil fuels to alleviate electricity deficits and meet growing demands from the road transport sector.[17] South Africa has nearly completed commissioning Medupi, the largest dry-cooled coal-fired power plant in the world (4.8 GW generating capacity).[18] Ghana and Mozambique recently purchased and commissioned offshore power plants (powerships). These run on bunker fuel, the residue from refining crude oil, that releases large quantities of SO_2 when burned.[19] South Africa and Namibia are also considering powerships as an interim solution to electricity shortages.[20,21] Motor fuel use for transport increased at a rate of 3.3% a^{-1} from 2006 to 2013.[14] Pollution from these sources will be further exacerbated by inadequate or absent environmental regulations across much of the continent.[22] Only South Africa has advanced air quality policy and monitoring, but compliance is not enforced.[23]

Here, we estimate premature mortality due to exposure to ambient $PM_{2.5}$ from future power plant and vehicle use by developing an inventory of present-day (2012) and future (2030) air pollutant emissions from these sources and implementing these in the GEOS-Chem chemical transport model (CTM), nested at high resolution over the African continent, to simulate $PM_{2.5}$.

2. METHODS

We calculate gridded power plant emissions in g a^{-1} for each generating unit x and air pollutant y ($E_{x,y}$) in Africa as follows:

$$E_{x,y} = 10^{-3} \times \frac{\lambda_x \times \gamma_x}{\eta_x} \times \sigma_x \times \Omega_{x,y} \tag{1}$$

where λ_x is the generating capacity (maximum power output) in GJ a^{-1}, γ_x is the fractional capacity factor, η_x is the thermal efficiency, σ_x is the stack gas volume in m^3 GJ^{-1}, and $\Omega_{x,y}$ is the stack gas concentration in mg m^{-3} of SO_2, NO_x, and primary particles (PM).[24] Stack gas volumes and concentrations are obtained under dry conditions at 1 atm, 10% excess O_2, and 25 °C for coal-fired power plants, and 3% excess O_2 for natural gas and crude oil. The emission factor of each unit (in g pollutant per GJ generating capacity) is therefore the product of the stack gas volume, σ_x, and stack gas concentration, $\Omega_{x,y}$.

Data we compile for present-day (2012) and future (2030) power plants in Africa are in Tables S1 and S2. We choose 2030 to accommodate the large variability in the time it takes for a power plant to progress from being announced to being operational (15 years for Medupi in South Africa versus 5 years for Jorf Lasfar in Morocco, for example). We use generating capacity, geographic coordinates, coal type, and status of current and future coal-fired power plants in Africa from the global Coal Tracker Database hosted online and maintained by the advocacy group "EndCoal" (https://endcoal.org/tracker/; last accessed 10 July 2019). We estimate present-day emissions for plants listed as operational in 2012 and future emissions using plants commissioned after 2012 or categorized by the EndCoal database as announced, permitted, planned, or under construction. We assume that coal burned is bituminous coal if this information is missing. Equivalent data for currently operational natural gas power plants is from the Global Energy Observatory (http://globalenergyobservatory.org/; last accessed 27 February 2019). There is no central database for future natural gas power plants, so instead we compile this information from multiple reports (references provided in Table S2). Our approach assumes that all power plants proposed as of November 2017 are commissioned and that there is no retirement of power plants operational in 2012. This is consistent with the proposed extension of power plants beyond their 50-year lifetime in South Africa, where the majority of coal-fired power plants in Africa are located.[25] We also include powerships in the future emissions estimate that have been suggested as an interim solution for electricity shortages in South Africa and Namibia. Powerships are already operating off the coasts of Ghana since 2015 and Mozambique since 2016 (Table S2).

Table S2 also includes the updated status of units as of July 2019, as we developed the inventory in 2017−2018. The generating units that have been shelved (delayed), canceled, or relocated (as is the case for one of the powerships in Ghana) comprise 12% of the total generating capacity in Table S2 (9% shelved, 3% canceled, 0.2% relocated). EndCoal assumes units are shelved if there has been no reported progress. Those canceled are due mostly to funding issues or, for Sibanye Gold Power Station in South Africa, a switch to solar energy. Power plants fully or partially operating as of July 2019 represent 41% of the total future generating capacity in Table S2.

We use the reported generating capacities (γ_x) in Tables S1 and S2 to estimate power plant emissions (Equation 1). Thermal efficiencies (η_x) are 33−43% for coal that varies with coal type;[26] 30−45% for natural gas that varies with turbine type;[27] and 31% for powerships.[27] Thermal efficiency of coal plants also varies by ∼30−40% with combustion type (subcritical, supercritical, and ultrasupercritical).[26] All generating capacity from coal in 2012 is from subcritical plants (η_x = 37%). Information on this is limited to a few of the future power plants that includes a mix of subcritical and supercritical (η_x = 40%) plants. Only Safi power plant in Morocco is ultrasupercritical (η_x = 45−48%). We use global mean capacity factors (γ_x), due to absence of this information for each plant. Values of γ_x are 58.5% for coal (2013−2015 mean value);[28] 6.3−52% for natural gas, dependent on turbine type (2013−2015 mean);[28] and 12% for powerships (2013−2015 mean value for steam turbines).[28] Stack gas volumes (σ_x) are 337.1 m^3 GJ^{-1} for hard coal, 360.6 m^3 GJ^{-1} for lignite, 272 m^3 GJ^{-1} for natural gas, and 279 m^3 GJ^{-1} for powerships.[29]

We use measured stack gas concentrations ($\Omega_{x,y}$) for SO_2 and NO_x (emitted as NO) from operating coal-fired power plants in South Africa.[30] For all others, we use 3270 mg m^{-3} for SO_2 and 1210 mg m^{-3} for NO_x,[30] the mean of the measurements for South African coal-fired power plants, where the majority of these are located in 2012 (92% of Africa's coal generating capacity; Table S1). For primary $PM_{2.5}$ from coal-fired power plants, we use a stack gas concentration of 78 mg m^{-3} based on the South African average for primary PM_{10} (180 mg m^{-3})[30] and a $PM_{2.5}$-to-PM_{10} ratio of 0.423.[31] For natural gas, we use stack gas concentrations of 2.5, 343, and 0.4 mg m^{-3} for SO_2, NO_x, and primary $PM_{2.5}$,[29] and for powerships, we use stack gas concentrations for heavy fuel oil: 4840, 699, and 57.3 mg m^{-3} for SO_2, NO_x, and primary $PM_{2.5}$.[29] We further partition primary $PM_{2.5}$ into 0.2% BC[32] and the remainder as dust. Our approach assumes emission abatement controls are limited to the bag filters or electrostatic

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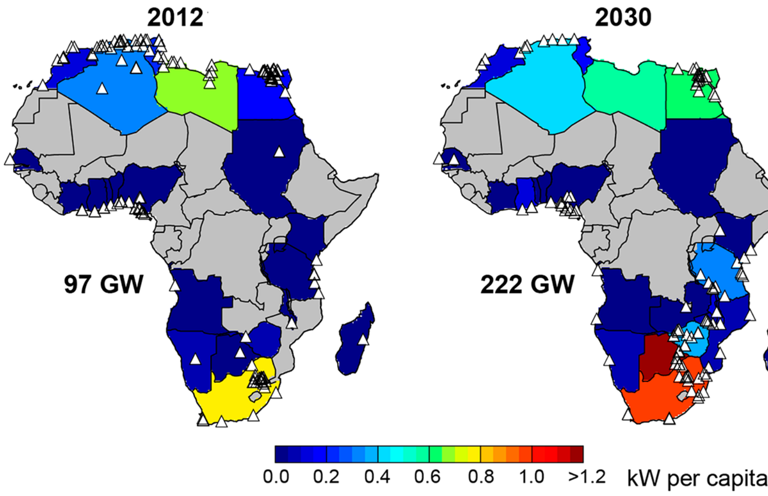

Figure 1. Generating capacity from fossil fuels in Africa in 2012 and 2030. Maps show per-capita generating capacity for each country and the locations (triangles) of fossil fueled power plants operational in 2012 (left) and added after 2012 (right). Population in 2030 is from the UN medium-variant population growth scenario.[3] Values inset are total generating capacity for the continent. Gray indicates countries with no reported coal or natural gas power plants.

precipitators installed in all South African power plants to remove particulates.[33]

Emissions from the vehicle fleet (including motorcycles) for 2012 are from the regional Diffuse and Inefficient Combustion Emissions for Africa (DICE-Africa) inventory.[14] DICE-Africa combines detailed ground- and space-based activity data and inefficient combustion emission factors relevant to Africa to address misrepresentation or absence of these sources in global inventories. Factors that can influence fuel usage for road transport, and hence emissions, include population growth, Gross Domestic Product (GDP), and household income.[34] We find that total population in Africa explains 96% of the variability in vehicle fuel usage in Africa, as determined by regressing motor gasoline consumption against total population from 2000 to 2016. Both data sets are from the UN data portal (http://data.un.org/Explorer.aspx; last accessed 10 June 2019). The motor gasoline data is the same as that used in DICE-Africa to determine total vehicle fuel (gasoline/petrol and diesel) usage.[14] For some countries, total population is a poor predictor ($R^2 < 0.4$) for motor gasoline usage, but these countries (Cape Verde, Djibouti, Eitrea, Gambia, Madagascar) make <10% contribution to total fuel usage in Africa. We go on to estimate vehicle emissions in 2030 by scaling gridded DICE-Africa vehicle emissions in 2012 by the relative change in population from 2012 to 2030 to represent a business-as-usual scenario informed by past behavior and with no policy interventions. The 2030 population projection is the UN[35] "medium-variant" population scenario that assumes a steady decline in fertility from 4.7 live births per woman in 2010–2015 to 3.1 in 2045–2050.[3]

We apply the vehicle and power plant emissions developed in this work to the GEOS-Chem CTM (version 10–01; http://wiki.seas.harvard.edu/geos-chem/index.php/GEOS-Chem_v10-01, last accessed 28 November 2017) to estimate surface concentrations of $PM_{2.5}$ for the present-day (2012) and future (2030). The model is driven with Goddard Earth Observing System–version 5 (GEOS-5) assimilated meteorology from the NASA Global Modeling and Assimilation Office (GMAO) at 0.5° × 0.667° (~50 km × 67 km; latitude × longitude) over Africa, the native horizontal resolution of the meteorology. This is nested within a global simulation at 2° × 2.5°.[36] Meteorology is for the year 2012 in both the present-day and future simulations to isolate the effect of a change in emissions on $PM_{2.5}$. Other anthropogenic emissions not estimated in this work or not in DICE-Africa (shipping, aviation, industry, agriculture) are from EDGAR version 3.2[37] Bond et al.,[38] Stettler et al.,[39] and Wiedinmyer et al.[15] Nonanthropogenic emissions in the model include biogenic VOCs (MEGAN version 2.1),[40] open savanna and crop fires (GFED version 4 without small fires),[41] lightning,[42] wind-blown dust (DEAD),[43] and natural and fertilizer-induced soil NO_x.[44] The model simulates mass concentrations of the dominant $PM_{2.5}$ components, sulfate, nitrate, ammonium,[45,46] OA,[47] BC,[48] dust,[43] and sea salt,[49] coupled to detailed gas-phase chemistry.[50] Partitioning of sulfate, nitrate, and ammonium between the gas and aerosol phase is determined thermodynamically,[51] and removal is via wet and dry deposition.[52,53] We sample the model following a 2-month spin-up for chemical initialization.

For our study, we focus on the health burden on people older than 14 years that result from exposure to ambient $PM_{2.5}$ from additional fossil fuel sources in 2030 relative to 2012. The number of premature deaths that result from this exposure is calculated as follows:

$$\Delta y_{i,j} = y_0 \times pop_{i,j} \times AF_{i,j} \quad (2)$$

where $\Delta y_{i,j}$ is the change in premature deaths in each GEOS-Chem grid square, i,j, due to a change in fossil fuel $PM_{2.5}$ from 2012 to 2030, y_0 is baseline mortality of people >14 years in each country due to all causes, the attributable fraction, $AF_{i,j}$, is the proportion of baseline mortality attributable to a change in gridded GEOS-Chem $PM_{2.5}$ from 2012 to 2030, and $pop_{i,j}$ is the gridded 2030 population older than 14 years. Details of the expression used to estimate $AF_{i,j}$ are provided in the Supporting Information.

Values of y_0 for individual countries are from the Global Burden of Disease for 2015 (https://vizhub.healthdata.org/gbd-compare/, last accessed 21 June 2018), $pop_{i,j}$ is estimated with total gridded population data from the Global Population Projection Grids Based on Shared Socioeconomic Pathways (SSPs)[54,55] for 2015 and 2030, and age distribution data for

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each country is from the UN for 2015 and 2030.[3] The gridded 2030 population is the middle-of-the-road population growth rate scenario (SSP2), and the projected 2030 age distribution for each country is the UN medium-variant population projection. The concentration−response function used to estimate $AF_{i,j}$ is from the meta-analysis of Vodonos et al.[56] The shape of the concentration−response function, shown in Figure S1, is nonlinear. That is, the health risk due to a unit change in $PM_{2.5}$ decreases as $PM_{2.5}$ increases. Additional details of the concentration−response function are in the Supporting Information.

The approach we use here to estimate emissions is informed by past behavior and so represents a business-as-usual scenario. An alternate approach is to obtain a range of health estimates based on a worst-case scenario that includes no air quality policy implementation and greater increase in emissions driven by economic prosperity and other factors and a best-case scenario where strict emission control measures are enforced. The response of annual mean $PM_{2.5}$ to perturbations in emissions is roughly linear,[57,58] so premature mortality of alternate scenarios could, to first order, be estimated relative to the values obtained in this work.

3. RESULTS AND DISCUSSION

Figure 1 shows the 2012 and 2030 per capita generating capacity in each country from coal, natural gas, and offshore (powerships) power plants. Also given is the total generating capacity for the continent: 97 GW in 2012, increasing to 222 GW in 2030. Generating capacity from coal and natural gas in the US, by comparison, totals 732 GW for summer 2012.[59] Per-capita generating capacity in each country in Figure 1 does not account for export of energy, such as occurs today from South Africa to neighboring countries.[25] If all proposed power plants become operational by 2030, generating capacity increases by 130% from 2012 to 2030, surpassing the rate of population growth (54%) over the same time period. Most of the future growth in generating capacity is in Southern and North Africa, where it is already relatively high. The increase in generating capacity (125 GW) is predominantly from coal (64 GW; 36% increase in Egypt, 24% in South Africa), followed by natural gas (58 GW; 32% increase in Egypt) and bunker fuel (3.3 GW). The relative contribution from coal and natural gas is similar in 2012 (44% coal, 56% natural gas) and 2030 (48% coal, 50% natural gas).

Total emissions from power plants in Figure 1 are 2.32 Tg SO_2, 1.04 Tg NO_x, and 0.05 Tg $PM_{2.5}$ in 2012, increasing to 5.31 Tg SO_2, 2.23 Tg NO_x, and 0.11 Tg $PM_{2.5}$ in 2030. Our power industry emissions for 2012 are less than those in the global EDGAR version 4.3.2 inventory[60] for the same year in Africa, even though EDGAR assumes implementation of abatement measures.[60] EDGAR total emissions are 2.87 Tg SO_2, 1.49 Tg NO_x, and 0.17 Tg $PM_{2.5}$ (http://edgar.jrc.ec.europa.eu/overview.php?v=432_AP, last accessed 7 January 2019). Emission factors for coal are all lower in the emission factor guidelines document used for EDGAR (820, 209, 3.4 g GJ^{-1} for SO_x, NO_x, and $PM_{2.5}$)[61] than those used in this work (1102, 408, 26 g GJ^{-1} for SO_x, NO_x, and $PM_{2.5}$). The emission factors used in this work are from smokestack measurements in South Africa (92% of coal generating capacity in Africa in 2012) and so represent realistic conditions for 2012. The difference in total emissions may then arise from the activity factors. EDGAR uses the CARMA v3.0 database to identify power plant locations, generating capacity, and fuel type. The CARMA database URL, www.carma.org, is no longer active. According to the CARMA v3.0 report,[62] CARMA uses variable capacity factors that often exceed the fixed value (59.3%) used here. Also, EDGAR 2012 power plants are mapped using information from CARMA for a different year (2014).[60]

South Africa accounts for 43% of total generating capacity on the continent in 2012. This decreases to a share of 28% in 2030. Our emissions for South Africa in 2012 (2.2 Tg SO_2, 0.84 Tg NO_x, 0.05 Tg $PM_{2.5}$) are higher than those obtained by Henneman et al.[63] for SO_2 and NO_x from power and heating plants in 2015 (1.9 Tg SO_2, 0.47 Tg NO_x, 0.05 Tg $PM_{2.5}$), estimated using the Greenhouse Gas and Air Pollution Interaction (GAINS) model. Pretorius et al.[25] estimated emissions from South African coal-fired power plants of ∼1.8 Tg SO_2 and ∼1.0 Tg NO_x for 2012 using reports of annual energy production and flue gas flow rates from the South African electricity utility, Eskom. Our emissions are 22% higher for SO_2 and 16% lower for NO_x than theirs due to differences in emission factors and capacity factors.

Total emissions from vehicles in 2012 are 0.17 Tg SO_2, 0.42 Tg NO_x, 1.36 Tg NMVOCs (40% aromatics; precursors of SOA) and 0.43 Tg $PM_{2.5}$ (0.04 Tg BC and 0.39 Tg OA), all increasing by 40% in 2030. The largest relative increase is in Niger where the population increases by more than 80% from 2012 to 2030. DICE-Africa NO_x from road transport is almost 5 times lower than that from EDGAR (1.89 Tg). Emission factors used in DICE-Africa are for inefficient combustion conditions that result in relatively low NO_x emissions,[14] whereas EDGAR v4.3.2 uses European road transport emission factors for Africa.[60,64] DICE-Africa OA emissions are mostly (>90%) from motorcycles and exceed OA emissions from EDGAR (0.04 Tg) by an order of magnitude. The OA emission factors in DICE-Africa are from measurements of motorcycles in West Africa[65] that are at least a factor of 4 higher than values reported for Europe.

Liousse et al.[66] projected 2030 emissions from all anthropogenic sources in Africa using an energy sector model to determine future fossil fuel use. They reported individual sector emissions for BC that increase by about a factor of 6 from 2005 to 2030 for both vehicles and power plants for a business-as-usual scenario. In our work, the increase is only 40% for vehicles and about a factor of 2 for power plants. We do not consider economic influences on vehicle ownership and therefore likely underestimate the increase in vehicle use. Our total BC emissions from power plants are also much lower (0.10 Gg in 2012, 0.22 Gg in 2030) than those in Liousse et al.[66] (20 Gg in 2005, 20−200 Gg in 2030, depending on future scenario). The difference in emissions of BC is in part due to much higher BC emission factors for coal in Liousse et al. (0.04−0.08 g kg^{-1}) compared to this work (∼0.002 g kg^{-1}, varying with coal type). The emission factors reported in Liousse et al.[66] are likely an error, as the BC emission factors for the power sector in the reference they cite (Bond et al.[67]) are 0.002−0.009 g kg^{-1}, consistent with the emission factors used here.

Other fossil fuel sources (diesel/petrol generators, flaring of natural gas, ships) are kept at 2012 levels. Generators may account for 19% of generating capacity in West Africa, and about half the generating capacity in the Democratic Republic of the Congo, Equatorial Guinea, and Mauritania.[68] Data on fuel use and emission factors from this source are very limited,[14] and future usage is challenging to predict, as it varies with household income, electricity access, and reliability of the

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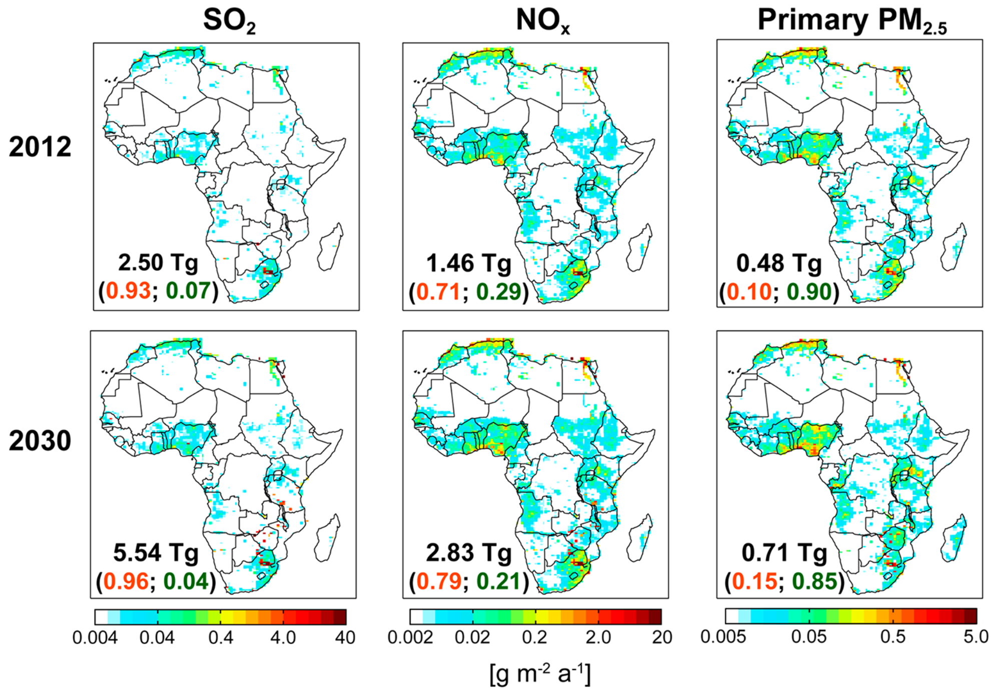

Figure 2. Air pollutant emissions from fossil fuels in Africa in 2012 and 2030. Gridded (0.5° × 0.667°) combined power plant and vehicle annual emissions of SO_2, NO_x, and $PM_{2.5}$. Data are on a log scale, and the colorbar range differs for each pollutant. Numbers shown inset are total emissions (black) and fractional contributions from power plants (orange) and vehicles (green) for the continent.

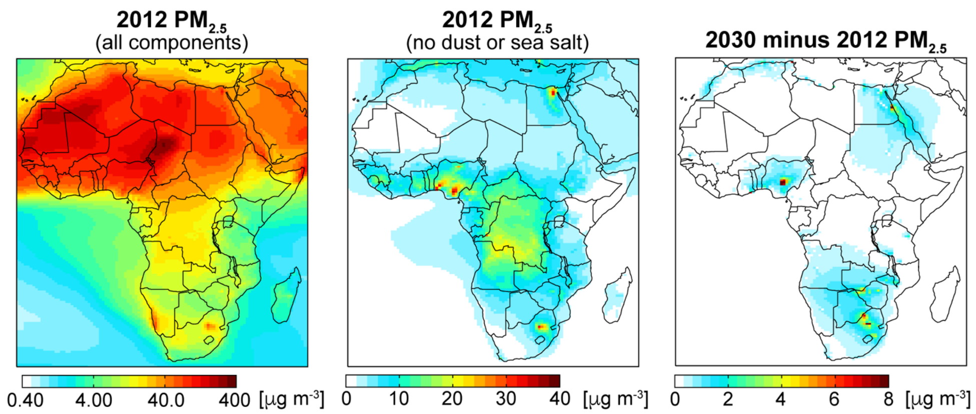

Figure 3. Impact of future fossil fuel emissions on annual mean $PM_{2.5}$. The panels show GEOS-Chem annual mean surface total $PM_{2.5}$ in 2012 (left; log scale), $PM_{2.5}$ excluding sea salt and dust in 2012 (center), and the change in $PM_{2.5}$ in 2030 relative to 2012 due to an increase in fossil fuel emissions from power plants and transport (right).

existing grid.[68] Space-based observations of gas flaring hotspots in Africa, mostly in the Gulf of Guinea and at oil/gas extraction sites in the Sahara Desert, provide a record of flaring activity.[5] Flaring in Africa decreased by 4.4% a^{-1} between 2006 and 2013, according to this record.[14] Air pollution from ships is expected to decline following International Maritime Organization (IMO) emission limits on NO_x, SO_2, and particles and further reductions of these in specific control areas (http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Air-Pollution.aspx; last accessed 23 July 2019).

Figure 2 shows the spatial distribution and total annual emissions of SO_2, NO_x, and primary $PM_{2.5}$ from power plants and vehicles in 2012 and 2030. Air pollutant emissions for individual fossil fuel plants are in Tables S1 and S2. Emissions of SO_2 more than double in 2030 relative to 2012, mostly from future coal-fired power plants across Southern Africa, in central Nigeria, and along the coast of Egypt. The diffuse increase in emissions of primary $PM_{2.5}$ (48% increase from 2012 to 2030) in populated areas is due to transport. Ship emissions of SO_2 (3.18 Tg) and NO_x (4.97 Tg NO), that we obtain by sampling the CEDS emission inventory[69] in 2012 up to 50 km from the African coastline, are higher than the 2012 land-based emissions in Figure 2. A shift in dominance of land-based emissions is likely by 2030 following successful implementation of ship emission regulations.

Figure 3 is the corresponding simulated annual mean $PM_{2.5}$ in 2012 with and without the contribution from dust and sea salt. Dust and sea salt are excluded to distinguish this overwhelming source of $PM_{2.5}$ from anthropogenic activity that is particularly intense in Egypt and Nigeria.[6] The diffuse enhancement in $PM_{2.5}$ in the Congo is from seasonal open fires. There are too few observations of $PM_{2.5}$ in Africa in 2012 to evaluate GEOS-Chem, as is evident from the dearth of

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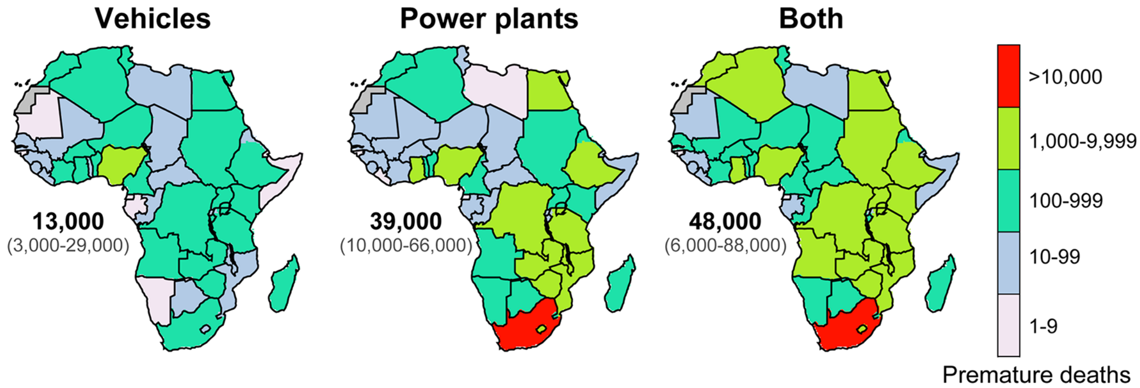

Figure 4. Impact of future fossil fuel use on mortality. The panels show the additional premature deaths in 2030 relative to 2012 in each country in Africa due to exposure to $PM_{2.5}$ from increased adoption of fossil fuels between 2012 and 2030 for vehicles (left), power plants (center), and the combination of the two (right). Numbers inset are continent-wide total premature deaths with 95% confidence intervals in parentheses.

measurements on the open-source data platform, OpenAQ (https://openaq.org). OpenAQ includes some sites in Africa from the SPARTAN network[70] and at US Embassies in Uganda and Ethiopia, but SPARTAN and Embassy measurements start after 2012. Instead, we use annual mean $PM_{2.5}$ from surface measurements along the South African Highveld quality controlled and reported in Garland et al.[71] (Figure S2) and the global satellite-derived $PM_{2.5}$ data set used extensively to determine the burden of ambient $PM_{2.5}$ on health (e.g., references 72−74) (Figure S3). The satellite product is derived with space-based observations of column integrated aerosol optical depth (AOD) and the modeled local relationship between column AOD and surface $PM_{2.5}$ from GEOS-Chem, followed by calibration with surface observations.[11] We find that our model results and the surface sites in South Africa are spatially consistent (R = 0.67), but the model is biased high (regression slope of 1.5 ± 0.3 and model normalized mean bias, NMB, of 35%). This is due to a large enhancement in modeled $PM_{2.5}$ (Figure S4) coincident with intense primary $PM_{2.5}$ emissions from trash burning in the model south of Johannesburg. The satellite product NMB is only 9.2% compared to the surface sites (Figure S4), but background $PM_{2.5}$ in the satellite product is overestimated (regression intercept of 10.4 ± 5.9) and the variance is underestimated (regression slope of 0.75 ± 0.2). Across Africa, the model and satellite product are consistent ($R = 0.89$) and the bias in the model is low compared to the satellite product (NMB = −8.2%) (Figure S3).

Figure 3 also shows the increase in GEOS-Chem $PM_{2.5}$ from 2012 to 2030 due to an increase in fossil fuel use. The additional power plants in South Africa and Botswana have widespread regional influence on $PM_{2.5}$ in Southern Africa, extending as far north as northern Angola. This is due to circulation of surface air from the Highveld in northeast South Africa, where power plants are concentrated, out over the Atlantic via Zimbabwe and northern Angola.[75] These particles travel farthest in the dry season (June-August) when $PM_{2.5}$ is long-lived. The increase in $PM_{2.5}$ along the South Africa/Botswana border is due to the Medupi dry-cooled power plant. Four of the six 800-MW units of Medupi (Table S2) began operating in the years since 2012 (https://www.sourcewatch.org/index.php/Medupi_Power_Station; last accessed 22 July 2019) alongside the already operational 4 GW Matimba plant (Table S1). Enhancements in column concentrations of SO_2 and NO_2 coincident with Medupi and Matimba are visible from the high-resolution space-based Sentinel-5P TROPOMI instrument (Figure S5). Medupi is only required to comply with SO_2 emission limits of new power plants (500 mg m^{-3} compared to 3500 mg m^{-3} for existing plants) by 2021, 6 years after it was commissioned (2015).[76] One of the 800-MW units at the Kusile plant (Table S2; location indicated in Figure S5) was also commissioned after 2012 (https://www.sourcewatch.org/index.php/Kusile_Power_Station; last accessed 22 July 2019) but was likely not operating during the TROPOMI observing period in Figure S5.[77]

The simulated 2030 enhancement in $PM_{2.5}$ in central Nigeria (Figure 3) is from the proposed Kogi Power Station. At the time of developing our inventory, this plant was to have a 1.2 GW generating capacity (Table S2), but this has since doubled to 2.4 GW (https://www.sourcewatch.org/index.php/Kogi_power_station#cite_note-powerchina-11). Kogi will be close to Abuja, one of the fastest growing cities in Africa, with a population increase from <1 million in 2006 to >5 million by 2030.[3] We find that the increase in $PM_{2.5}$ in Nigeria is greatest in the dry season (December−February), when $PM_{2.5}$ has a long lifetime and pollution accumulates due to a natural inversion induced by the warm Harmattan winds.[6] In the wet season, the southwesterlies from the West African Monsoon more efficiently ventilate the region.[6]

GEOS-Chem also simulates surface concentrations of ozone, formed from photochemical oxidation of VOCs or CO in the presence of NO_x. Ozone affects human health and is toxic to crops at concentrations >40 ppbv.[78,79] The 2012 concentration and change in 24 h mean surface ozone in 2030 relative to 2012 due to an increase in fossil fuel emissions is in the Supporting Information (Figure S6). Global premature mortality from exposure to ozone is much less than that from exposure to $PM_{2.5}$ (254000 from ozone compared to 4.5 million from $PM_{2.5}$ in 2015).[80] Models that account for exposure to both $PM_{2.5}$ and ozone find that ozone increases the risk of death from respiratory causes only and the increase in risk is just 4% (95% confidence interval or CI: 1.3−6.7%) per 10 ppb ozone.[79] NO_x from power plants actually titrate ozone in densely populated areas in Nigeria, Egypt, and South Africa, causing a local 2−3 ppbv decrease in ozone. Africa is particularly vulnerable to crop loss, as agriculture is often a large (>10%) contributor to GDP in many African countries.[81] Ozone already exceeds levels safe for vulnerable crops (~40 ppbv) in North Africa and is close to this threshold across

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Southern Africa, where ozone in 2030 could be ~3 ppbv more than in 2012.

Figure 4 shows the resultant premature deaths in each country due to an increase in fossil fuel $PM_{2.5}$ from vehicles only, power plants only, and the combination of the two. Continent-wide mortality from both sources is 48000 people (95% CI: 6000−88000) and is highest for the combination of both sources in South Africa (10,400; 95% CI: 2000−18300) where power plant emissions are high, and in Nigeria (7500; 95% CI: 1300−23800) where the population growth rate from 2012 to 2030 is 2.8% a^{-1}. Mortality attributable to $PM_{2.5}$ from vehicle emissions is 3-times less than that from power plants due to the relatively lower emissions of the $PM_{2.5}$ precursors SO_2 and NO_x (Figure 2).

The ten countries with the highest premature mortalities, ranked in Table S3, account for 70% of premature deaths in Africa. The table also includes the corresponding increase in $PM_{2.5}$ and population >14 years from 2012 to 2030. Most countries listed in Table S3 are in the southeast portion of Africa (South Africa, Malawi, Zambia, Zimbabwe, Lesotho) where planned coal-fired and natural gas power plants (Figure 1) total 42 GW. This accounts for 34% of generating capacity to be added from 2012 to 2030. The confidence intervals for Egypt and Nigeria in Table S3 are relatively wide, as average $PM_{2.5}$ in those countries and across West and North Africa in general is higher (>40 $\mu g\ m^{-3}$; Figure 3) than the range of average $PM_{2.5}$ from the cohort studies used to derive the concentration−response function used in this work (Figure S1). Population projections for 2030 in Africa range from 1.4 to 1.8 billion people,[3] so our estimate of premature deaths will be sensitive to assumed population growth. If instead we use the 2030 projection assuming slow economic and high population growth (SSP3), premature mortality for Africa is 51000; 6% more than that obtained with the SSP2 population growth scenario.

Table S3 also includes the change in $PM_{2.5}$ relative to the change in population >14 years ($\Delta PM_{2.5}/\Delta pop$) that could be used as an indicator for assessing sensitivity of future mortality estimates to uncertainties in air quality, population, or both. For $\Delta PM_{2.5}/\Delta pop > 0.1$ (South Africa, Malawi, Zambia, Zimbabwe, and Lesotho), mortality estimates are most sensitive to uncertainties in air pollution, whereas at $\Delta PM_{2.5}/\Delta pop < 0.1$ (Nigeria, the DRC, Egypt, Tanzania, and Ethiopia), mortality estimates are most sensitive to uncertainties in population projections.

The premature deaths attributable to future fossil fuel emissions that we estimate in this work is at least a factor of 10 fewer than premature mortality attributable to exposure to ambient $PM_{2.5}$ from natural sources (mostly windblown Saharan dust) of 648000 for age groups <5 years and ≥30 years[82] and 782000 for all age groups.[12] These were obtained at spatial resolutions of 1.1° × 1.1°[12] and 2° × 2.5°,[82] coarser than in this work (0.5° × 0.667°). We only consider the portion of the population older than 14 years, as this is consistent with the data used to derive the exposure-response relationship used in Equation 2.[56] Excess deaths attributable to exposure to air pollution from all sources for infants in utero and up to 12 months in Sub-Saharan Africa may be as much as 449000 per year, mostly in locations with high dust loading.[83]

Our estimate of 48000 premature deaths due to exposure to $PM_{2.5}$ from future fossil fuel sources is on the low-end of the range of present-day (2015) premature mortality in Africa (79000; 95% CI: 41000−178000) attributable to $PM_{2.5}$ from all fossil fuel sources on the continent and abroad (mostly Europe).[2] This suggests that the contribution of anthropogenic sources in Africa will increase relative to external sources, enhanced by decline in use of diesel cars in Europe[84] and a gradual shift in Europe to renewable energy.[85] Lacey et al.[16] projected future (2030) emissions from all anthropogenic sources in Africa by scaling emissions for 2006 by national demographic and economic projections and applied this to the adjoint of the GEOS-Chem model. They estimated fewer premature deaths (35000) in Africa in 2030 from the energy sector than that obtained here, as our projected generating capacity surpasses population growth. They went on to project that 11000 deaths could be avoided by switching 50% of energy production to renewables. Our work suggests a larger health benefit of shifting to clean energy sources in Africa.

The deleterious effects of future fossil fuel use for power generation and transport could be offset by increased electrification in Africa leading to reduced exposure to indoor air pollution from burning wood and charcoal.[86] Past behavior, however, does not support the theory that traditional energy practices decrease with increase in electrification. Percent population with access to electricity in Sub-Saharan Africa has increased from 26% in 2000 to 45% in 2017 (a rate of 1% a^{-1}), according to data obtained from the World Bank (https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS; last accessed 16 July 2019). At the same time, charcoal use in Africa has increased by 7% a^{-1} from 2000 to 2014 according to data provided by the UN (http://data.un.org/Explorer.aspx; last accessed August 2017) and fuelwood use by 1.3% a^{-1} in the residential sector and 4.3% a^{-1} in the commercial sector from 2006 to 2013, according to activity factor data from the DICE-Africa inventory.[14]

4. UNCERTAINTIES

Below, we discuss the largest sources of uncertainty to our estimated premature mortality estimates. Our future emission projections for power plants assume no adoption of best-available abatement technology. In cases where funding is sought from multilateral development banks, like World Bank, power plants are required to use high-efficiency low-emissions technology. In 2014, funding by these development banks accounted for just 6% of global investment in coal-fired power plants, although other banks are considering adopting similar loan conditions.[87] Adopting the latest abatement technology for existing and recently commissioned (Medupi and Kusile; Table S2) coal-fueled reactors in South Africa could reduce emissions by 50% for particulates, 10% for NO_x, and 30% for SO_2.[25] This requires effective enforcement that does not appear to be achieved in South Africa. The 4.1 GW Kendal plant (Table S1), for example, has had faulty emission technology for over a year.[88]

The emission projections for vehicles that depend on population growth only also assume no change in the proportion of diesel and petrol use or in emission factors that may result from new technology or successful implementation of emission regulations. Some policies are either in place or under consideration for regulating fuel sulfur content, imposing limits on the age of imported used vehicles, and promoting or limiting import of high-sulfur fuel and second-hand diesel vehicles from Europe. Implementation dates, enforcement, and adoption by African countries are highly variable.[89−91]

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Large sources of uncertainty in the health calculation include baseline mortality (y_0 in Equation 2) and the relationship between health risk and ambient $PM_{2.5}$ (the concentration−response function).[92] Record keeping and reporting on health statistics in Africa are limited.[93] We use the same (2012) baseline mortality for 2012 and 2030. In 2012, in Sub-Saharan Africa, health risks associated with poverty and under-development dominate and are forecasted to persist into 2040.[94] The nonlinear concentration−response function used here (Figure S1) yields higher relative risks than the Integrated Exposure-Response (IER) function used in Global Burden of Disease studies.[95] It results in premature mortality estimates that are at least a factor of 2 more than the IER,[74] as it was developed with the inclusion of cohorts from Asia that were exposed to $PM_{2.5}$ > 40 $\mu g\ m^{-3}$.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.9b04958.

Description of the attributable health calculation; the shape of the concentration−response function, evaluation of GEOS-Chem $PM_{2.5}$; satellite observations of NO_2 and SO_2 over South Africa; and maps of GEOS-Chem surface ozone in 2012 and the change in 2030 relative to 2012 (PDF)

Location, generating capacity, air pollutant emissions, and data sources of power plants operating in 2012; operating, commissioned, undergoing construction, or proposed after 2012; air pollution, mortality, and sensitivity metrics for the 10 countries with highest mortality (XLSX)

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E.A.M. conducted the GEOS-Chem model simulations, vehicle emission projections, data analysis, and prepared the manuscript. R.F.S. compiled the power plant emission inventory; E.D. analyzed the motor gasoline data and generated plots; L.J.M. provided guidance and assisted in the writing; A.V. and J.S. estimated the health effects; A.S.B. conducted the charcoal use trend analysis.

Notes

The authors declare no competing financial interest.

GEOS-Chem annual mean surface concentrations of $PM_{2.5}$ and ozone are available for download (http://maraisresearchgroup.co.uk/Data/gc-pm25-ff-emis.tar.gz, http://maraisresearchgroup.co.uk/Data/gc-ozone-ff-emis.tar.gz). Data and code for the health burden meta-analysis are available on GitHub: https://github.com/AlinaVod/meta_regression_pm2.5. Gridded emission inventory data and GEOS-Chem model source code can be requested from E.A.M.

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