Sustainable Energy Transitions in sub-Saharan Africa: Impacts on Air Quality, Economics, and Fuel Consumption

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Abstract

Historically, the United States, Europe, and China have produced the most greenhouse gas (GHG) emissions, with the largest share (25%) coming from the electricity and heating sector. With declining growth rate projections and access to electricity services all near or at 100%, developed countries have increased their share of sustainable energy sources such as wind and solar power. Unlike the most developed nations, populations are expected to increase drastically throughout the developing world in the 21st century. Recent estimates indicate 97% of the world's population growth through 2030 (1.3 billion more people) will occur in the developing world. The countries of sub-Saharan Africa alone are projected to add over a billion people through 2050. Such population growth in developing countries will result in growing energy demand and thus growing emissions. The United Nations has underscored the importance of ushering in responsible and equitable energy pathways through their Sustainable Development Goals (SDGs). With a set of goals emphasizing access to affordable and reliable power, access to modern energy services, and reducing poor air quality and GHG emissions, the SDGs aim to improve quality of life across key areas of concern. The aim of this dissertation is to identify and evaluate opportunities for avoiding continued increases in fossil fuel use in sub-Saharan Africa, which would in turn reduce and avoid emissions of greenhouse gases and criteria air pollution and reduce some associated costs.

In Chapter 2 we analyze the energy, emissions, and consumer costs of power outages in sub-Saharan African countries. By modeling the fuel mix for the central electricity grid in each country and the diesel fuel needed to produce backup electricity during outages, we estimate the magnitude of these impacts in the region. We show that use of backup generators leads to higher fossil energy consumption (compared to the central grid) in all countries, even countries that already rely on fossil fuels for power generation at centralized plants. Furthermore, for all countries in the analysis, backup diesel generators result in increased mean emissions of at least three of the five pollutants analyzed, compared to the grid. Our analysis highlights the magnitude of potential avoided emissions and economic savings from increased grid reliability, and has implications for achieving Sustainable Development Goals. Increased reliability may not

lead to decreases in generator ownership, but it is likely to lead to decreases in generator use, thus avoiding additional emissions and reducing costs for consumers.

In Chapter 3 we assess the emissions, health, and economic outcomes of electrifying motorcycle taxis in Kigali, Rwanda. By modeling fleet demand using observed driving distributions, we are able to estimate travel of this unique subset of all motorcycles which form the basis for all estimates. Our analysis reveals that emissions of key pollutants already identified by government officials (NOx, CO, HCs) as well as the greenhouse gas CO_2 and health risks from $PM_{2.5}$ can be drastically reduced via motorcycle fleet electrification. While a reduction of primary and secondary $PM_{2.5}$ exposure and thus deaths can be achieved with the electrification of motorcycles, such benefits are dependent on the marginal generating unit. Finally, the Levelized Costs of Driving analysis reveals that at least one of the electric motorcycle alternatives presented in this work is cost competitive over a five-year period, and cost competitiveness improves as vehicle life is extended.

In Chapter 4 we extend the vehicle electrification analysis to assess the benefits and costs of bus electrification in Rwanda. We employ a Monte Carlo Analysis to assess how the emissions, health impacts, and non-infrastructure costs associated with diesel powered buses compare to those associated with their electric counterparts. We find that mean emissions of CO_2, $PM_{2.5}$, NOx, CO, and HC all decline significantly when travel provided by diesel buses is replaced with electric buses. However, we also observe increased emissions of SO_2 with bus electrification due in part to the prevalence of heavy fuel oil and peat electricity generation. Despite this increased SO_2, the health analysis reveals that electrification can result in less annual deaths from primary and secondary $PM_{2.5}$ but not if peat is the marginal electricity generating unit. Our economic analysis shows that electric buses have greater present levelized costs but given a decrease in capital cost and longer lifetime, electric buses can reach parity with the diesel buses. The final analysis in this chapter compares the normalized emissions and costs of conventional motorcycles, electric motorcycles, conventional buses, and electric buses. We find that the electric buses offer the greatest emission reductions (per passenger-kilometer) while the diesel buses offer the cheapest levelized costs. This research highlights the important role public transit electrification could play in achieving the Sustainable Development Goals as countries commit to lower greenhouse gas and harmful air pollutant emissions

Finally, in Chapter 5 we discuss the important role developing countries will play in achieving global sustainability as their population, mobility, and electricity usage rise over the coming decades. We discuss the implications that reliable power and electrification efforts could have for the Sustainable Development Goals and urge developed nations to assist developing countries in implementing some of the technologies necessary for their completion. This thesis provides the framework for policy makers throughout SSA to assess the benefits and costs associated with modernizing their electricity systems.

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Chapter 1: Motivation

Historically, the United States, Europe, and China have produced the most greenhouse gas (GHG) emissions with the largest share (25%) coming from the electricity and heating sector[1,2]. With declining growth rate projections in these countries through 2100 and access to electricity services all near or at 100%, developed countries have increased their shares of more sustainable energy sources such as wind and solar power[3,4]. As the historic leaders in electric and transportation sector emissions plan reductions in fossil-fuel based energy consumption, there has been increasing concern about enabling more sustainable development pathways for the rest of the world. Unlike the most developed nations, populations are expected to increase drastically throughout the developing world in the 21st century. Recent estimates indicate 97% of the world's population growth through 2030 (1.3 billion more people) will occur in the developing world[5]. Such population growth in developing countries will result in growing energy demand.

The United Nations has underscored the importance of ushering in responsible and equitable energy pathways through their Sustainable Development Goals[6]. With a set of goals emphasizing access to affordable and reliable power, access to modern energy services, and reducing poor air quality and greenhouse gas emissions, the SDGs aim to improve quality of life across key areas of concern. The seventh goal (SDG 7) calls for universal access to affordable, reliable, sustainable and modern energy for all by 2030[6]. The third goal (SDG 3) aims to ensure healthy lives and promote well-being for all ages with SDG 3.9, a more detailed target of SDG 3, calling for a reduction in morbidity and mortality from pollution[6]. Air quality is of particular concern in sub-Saharan Africa (SSA), where over 450,000 infant deaths each year can be attributed to poor air quality[7]. In rural areas, one of the largest sources of air pollutants is likely biomass burning for cooking[8]. However, in urban areas fossil fuel combustion is likely becoming a major source of air pollution (and costs to consumers).

A summary of the UN Sustainable Development Goals for 2030[6]:

1) No poverty	2) Zero hunger	3) Good health and well being	4) Quality education
5) Gender equality	6) Clean water and sanitation	7) Affordable and clean energy	8) Decent work and economic growth
9) Industry, innovation, and infrastructure	10) Reduced inequalities	11) Sustainable cities and communities	12) Responsible consumption and production
13) Climate action	14) Life below water	15) Life on land	16) Peace, Justice, and strong institutions
17) Partnerships for the goals			

Population growth and urbanization in SSA are a concern as the total population is expected to double from about 1 billion to over 2 billion in the next 50 years[9]. With that population growth, demand for electricity in SSA is also expected to grow, with some estimates projecting a 400% increase (over 2010's demand) to 1,600 terawatt hours (TWh) by 2040[10]. It is important to note that even this projected demand falls short of full electrification, and only accounts for electrification across 70-80% of households[10]. Much of the potential supply could come from solar (over 11,000 GW), however, other low carbon sources such as hydro (350 GW), wind (109 GW), and geothermal (15 GW) could also play a role[10]. Excluding solar power, the majority of potential supply comes from fossil fuels with natural gas and coal accounting for 400 GW and 300 GW, respectively[10]. However, this potential is yet untapped and frequent power outages are common to large percentages of the SSA population.

In addition to electricity generation, energy for transportation accounts for a considerable share of GHG emissions and local air pollutants throughout the world. Global passenger vehicle transport currently accounts for about 14% of greenhouse gas emissions[11]. While developed countries account for the vast majority of transportation emissions, developing countries' transportation emissions will rise as passenger vehicle ownership increases[11]. In sub-Saharan Africa (SSA), gasoline-powered motorcycles and minibuses represent a considerable share of passenger vehicle growth and also provide formal and informal taxi services[12,13]. The simultaneous expansion of the electricity and transport sector in SSA provides an opportunity for technology leapfrogging and electrification of historically fossil-fueled transport. In the near-term, electrification of transport could provide a path for reduced GHG emissions, air pollutant emissions, and fossil fuel use in SSA, which aligns with achieving Sustainable Development Goals 3, 7, 11, and 13.

The combination of low electricity access rates, a rapidly increasing population, increases in transportation demand, and large potential electricity demand pose serious yet surmountable challenges to ensuring sustainable development throughout the region. The aim of this dissertation is to identify and evaluate opportunities for avoiding continued increases in fossil fuel use in sub-Saharan Africa, which would in turn reduce and avoid emissions of greenhouse gases and criteria air pollution. Such transitions may also reduce the economic costs to consumers. Through this thesis research, I investigate the following research questions:

Chapter 2: Sustainability implications of electricity outages in sub-Saharan Africa

- To what extent do power outages alter fossil fuel consumption for electricity generation throughout sub-Saharan Africa?
- How does this change in fossil fuel consumption affect air pollution emissions throughout the region?
- What are the costs associated with backup diesel generation and how do they compare with grid-based generation?

Chapter 3: Motorcycle-taxi Fleet electrification in Kigali, Rwanda

- How do tailpipe emissions from conventional motorcycles compare with power plant combustion emissions associated with electric motorcycles in Kigali, Rwanda?
- What are the health impacts associated with emissions from conventional motorcycles compared to those of electric motorcycles?
- What are the non-infrastructure levelized costs associated with motorcycle fleet electrification?

Chapter 4: Electrification of multi-passenger transportation vehicles in Kigali, Rwanda

- How do tailpipe emissions from conventional diesel buses compare with power plant combustion emissions associated with electric buses in Kigali, Rwanda?
- What are the health impacts associated with emissions from conventional buses compared to those of electric buses?
- What are the non-infrastructure costs associated with transit system electrification?
- How do the emissions and costs from multi-passenger transportation vehicles electrification compare to that of motorcycle electrification?

Chapter 2: Sustainability implications of electricity outages in sub-Saharan Africa

The chapter uses “we” instead of “I” to reflect the contributions of my co-authors.

In this chapter we explore the impacts that power outages have on several countries in SSA that have varying levels of access to electricity. Unlike many developed countries, power outages can be a regular occurrence in some SSA countries. While these outages certainly effect the daily lives of SSA citizens, they also can have implications on sustainability efforts as the population and electricity consumption rises in the region. We examine how power outages effect fossil fuel consumption, emissions, and the cost of electricity in the region. Specifically, we answer the following questions:

- To what extent do power outages alter fossil fuel consumption for electricity generation throughout sub-Saharan Africa?
- How does this change in fossil fuel consumption affect air pollution emissions throughout the region?
- What are the costs associated with backup diesel generation and how do they compare with grid-based generation?

2.1 – Introduction

In 2015 the United Nations set an agenda designated as “Sustainable Development Goals” (SDG), which outline a framework for responsible and equitable development throughout the world[6]. The seventh goal (SDG 7) calls for universal access to affordable, reliable, sustainable and modern energy for all by 2030[6]. Currently, more than one billion people in the world lack access to electricity with the majority, about 634 million people, residing in sub-Saharan Africa (SSA)[14]. The various challenges of achieving electricity access in SSA are well documented. Challenges such as the need for productive electricity use frameworks[15,16], lack of cost recovering tariffs[17], unreliable supply[18], lack of investment[19,20], systemic infrastructure issues[21], and shortcomings in research[22] hamper the ability to achieve universal access.

A growing body of academic work focuses on evaluating strategies for expanding electricity access in sub-Saharan Africa[23–28]. Historically, many non-government organizations (NGOs) and multinational commissions have focused on increasing electricity access to unelectrified populations using binary indicators based on availability of an electricity connection[29,30]. While establishing an initial connection is important, SDG 7 establishes reliability as an essential component to the definition of access (SDG 7.1), and the World Bank has developed a multi-tier definition of energy access that accounts for level of service and reliability[29]. Unfortunately, many countries where access is increasing face electricity blackouts and brownouts due to capacity shortages and infrastructure failures[31]. The World Bank reports that countries in SSA experience annual outages ranging from 50 to 4,600 hours[32]. As a result, some of the population that purportedly already has access to grid electricity also regularly lose power, with some relying on small backup generators that are typically powered by diesel fuel. In some cases, backup diesel generators can account for up to 20% of a country's available electricity capacity[33,34]. Table 2.1 summarizes electricity access and outage information for selected countries where data are available in SSA.

Table 2.1: Electricity outage data for the SSA countries in our analysis[32]. Backup generator availability is reported as a percentage of the installed grid capacity. Generator capacity reported in this table include the mode and the min and max (in parenthesis) of the distribution[34] (See method section for more information). Population, electricity access, and installed capacity data are for 2014. All other data represent the most recent values reported.

Country	Population (millions)[38]	Access to Electricity (% of population)	Number of electrical outages in a typical month	Duration of a typical electrical outage (hours)	Average Annual Outage Hours	Installed Capacity of the Grid (GW)	Back-up generator availability (as percentage of grid capacity)
Angola	25.02	32	4.7	13.5	760	1.7	8% (1%-25%)
Cameroon	23.34	56.8	7.6	8.7	790	1.6	1% (1%-51%)
Cote d'Ivoire	22.70	61.9	3.5	5.5	230	1.8	6% (1%-22%)
Democratic Republic of the Congo (DRC)	77.27	13.5	12.3	5.6	830	2.6	46% (1%-51%)
Ethiopia	99.39	27.2	8.2	5.8	570	2.4	1% (1%-12%)
Ghana	27.41	78.3	8.4	7.8	790	2.8	12% (1%-22%)
Kenya	46.05	36	6.3	5.6	420	2.2	7% (1%-12%)
Mozambique	27.98	21.9	1.6	4.3	80	2.6	1% (1%-25%)
Niger	19.90	15	22	5.2	1,400	0.18	20% (1%-22%)
Nigeria	182.2	56.4	32.8	11.6	4,600	10.5	22% (1%-22%)
Senegal	15.13	61	6	1.8	130	0.96	1% (1%-25%)
South Africa	54.96	86	0.9	4.5	50	46	2.5% (1%-25%)
Tanzania	53.47	18.9	8.9	6.3	670	1.2	12% (1%-12%)
Zambia	16.21	27.9	5.2	2.8	180	2.3	3% (1%-25%)
Zimbabwe	15.60	32.3	4.5	5.2	280	2.1	5% (1%-25%)

Due to the cost of diesel fuel and the relative inefficiencies of small generators, backup diesel generator use can also result in increased costs of electricity for customers, which is detrimental to meeting SDG 7.1. For example, costs of electricity supplied by diesel generators can be three times that of grid electricity. While the overall economic impact of this increased cost is small when compared to avoided losses (e.g. spoiled goods and business interruption) during power outages[18], the value of unsupplied electricity and the costs of backup electricity may be considerable enough that they restrict the abilities of firms to grow[35]. Furthermore, the effects of power outages are not limited to business owners, and the increased costs of electricity for residential customers resulting from unreliable power could affect household budgets, which could be particularly detrimental for lower-income households[36].

Sustainable Development Goal 3 is to ensure healthy lives and promote well-being for all ages. SDG 3.9 calls for a reduction in morbidity and mortality from pollution. Relying on diesel backup generators in large numbers could increase emissions and exposure to air pollutants. Previous studies in the context of developed countries have illustrated the emissions and health impacts of diesel generator exhaust[37,38]. Gilmore et al. (2010) identify the cost-effectiveness of using backup diesel generators to satisfy peak electricity demand in major American cities but suggest that emissions controls are necessary to avoid health and air quality degradation[39]. In addition to cardiac and respiratory damages, the U.S. Environmental Protection Agency identifies diesel generator exhaust as a likely carcinogen[40]. In the context of African countries, recent estimates indicate that exposure to fine particulate matter in SSA led to an additional 449,000 infant deaths in 2015, accounting for 22% of infant deaths in total[7]. While African countries lack robust air quality monitoring networks or air quality models that can be used to assess the contribution of different sources of pollution to health impacts[41], concerns of adverse health impacts and environmental degradation have led to calls for greater regulation of diesel generators[42,43]. Thus reliance on diesel generators for backup power is detrimental to meeting SDG3.

In this chapter, we quantify the net air emissions (carbon dioxide, CO_2; fine particulate matter, $PM_{2.5}$; carbon monoxide, CO; sulfur oxides, SOx; and nitrogen oxides, NOx), fuel costs, and changes in fossil energy consumption that result when diesel generators are used to supply electricity during power outages in SSA. We perform a first order estimate of power system emissions for countries in SSA derived from power sector fuel consumption and electricity generation data. Using data on power outage frequency and duration by country, we then contrast grid level emission estimates with those of diesel backup generators used to provide electricity during outages. We use a Monte Carlo Analysis (MCA) framework to capture the uncertainty surrounding the proportion of generator ownership, total electricity load lost during power outages, and emissions factors within each country. Costs of purchasing fuel and the associated fossil energy changes are estimated from the diesel fuel necessary to provide this backup power.

2.2 – Methods

This chapter focuses on some of the most populous countries in sub-Saharan Africa (listed in Table 2.1). Of the most populous countries, we exclude Uganda, Sudan, Madagascar, Burkina Faso, Malawi, and Mali due to a lack of sufficient and consistent data. Table 1 contains the World Bank electrical outage data for the 15 countries in our analysis. The World Bank Enterprise Survey[32] provides insight into the magnitude of power outages in SSA. As expected, the range of outages (hours of outage per year) varies greatly across the region: according to the World Bank data, countries such as South Africa and Mozambique experience a relatively smaller number of outages, while Nigeria experience outages for more than one-third of the hours each year. However, the frequency and duration of power outages is not necessarily indicative of a nation's access to electricity. For example, although both South Africa and Mozambique rarely face outages throughout the year, 86% of South Africa's population has access to electricity while only 21.9% of Mozambique's population does[4]. Our analysis in this paper focuses on the use of backup generators by customers who already have connections to the grid.

The World Bank Enterprise Survey data provides the number of outages per year and the average duration of the outages, which we use to calculate the number of outage hours in a year. It does not, however, indicate the amount of load (MW) or generation (MWh) lost, nor does it include data on which electricity infrastructure components fail (specific plants, type of generation, transmission, or distribution). Data on the amount of load lost and subsequently replaced with backup generators are needed to estimate the associated emissions. In the absence of such data, we perform a Monte Carlo Analysis in which the load replaced during outages is bounded by a distribution of backup capacity available in each country. The sum of the load replaced during all outages in a year is equivalent to the distribution of installed diesel generator capacity multiplied by the number of outage hours, as described by Equation 2.1.

$$\sum_{t=0}^{t=i} \boldsymbol{x_t} = (\boldsymbol{\alpha C}) \times (\boldsymbol{i}) \qquad (2.1)$$

Where x_t is the amount of load lost at hour t, i is the number of outage hours, α is the percentage of the backup capacity in the system (treated as a triangular distribution), and C is the installed capacity of the grid, in MW. The distribution of backup capacity is bounded from 1% of installed capacity to the maximum observed regional value (as % of grid capacity) with the mode as the current estimate of installed backup capacity[34]. Table 2.1 summarizes the values we used for the triangular distribution of backup availability for each country. While it is possible that load lost during outages could go unreplaced, there are no robust data available to estimate such unmet demand. We thus argue that the Monte Carlo-based estimate of load replaced with backup generators captures the range of outcomes and is the best estimate given data availability.

Furthermore, we model these outages as averages over each country's specific generation mix. This means if a country generates 70% of its electricity from coal and 30% from natural gas, a 10% load loss corresponds to a loss of 7% of the coal generation and 3% of the natural gas generation. We use average generation rather than average capacity because capacity can go unused but generation is proven electricity production. Scenarios may occur when particular plants or technologies fail, (e.g. coal generation fails while natural gas plants continue to operate). In such cases, the average emission factors we use would not accurately reflect the reduction in grid emissions. This limitation notwithstanding, we believe our analysis is the first to characterize the potential magnitude of the effects of outages in most countries in our

SSA subset and can help inform decision-making on achieving Sustainable Development Goals.

Fossil fuel energy consumption differentials are calculated as follows. Each country's electrical generation data contained energy consumed by generation type. For example, 24 PJ of energy is consumed to produce electricity from natural gas in Ghana. We isolate the fossil fuel energy consumed per kWh of electricity produced and compare it to the level of fossil fuel energy necessary to provide commiserate levels of electricity from diesel generators during power outages. The calculation of these differentials is conducted as shown in Equation 2.2.

$$\Delta \boldsymbol{FE} = \boldsymbol{HR_{backup}} - \boldsymbol{HR_{grid}} = \frac{\mathbf{3.6}}{\eta_{backup}} - \frac{\mathbf{3.6}}{\eta_{grid}} \qquad (2.2)$$

Where HR_{grid} is the average heat rate of the grid, and indicates the fossil energy consumed by the grid (MJ) to generate one kWh, and HR_{backup} indicates the heat rate of diesel generators, and indicates fossil energy consumed by backup diesel generators (MJ) to generate one kWh. The fossil energy consumed to generate one kWh, also known as the heat rate, is equal to 3.6 MJ divided by the efficiency ($\boldsymbol{\eta}$) of the generators. For the backup diesel generators, we treat a $\boldsymbol{n_{backup}}$ as a triangular distribution between 20% and 35%. $\boldsymbol{\eta_{grid}}$ is a weighted average fossil fuel use efficiency for each country derived as:

$$\boldsymbol{\eta_{grid}} = \frac{\textbf{Annual Eletricity Generation From All Sources (in MJ of electricity)}}{\textbf{Annual Fossil Fuel Use (in MJ)}} \qquad (2.3)$$

Our analysis estimates emissions of carbon dioxide (CO_2), nitrogen oxides (NOx), carbon monoxide (CO), sulfur oxides (SOx), and fine particulate matter ($PM_{2.5}$) from power plants, allowing comparison to the emissions from diesel generators used to generate backup electricity. We estimate emissions by multiplying emissions factors (kg of emissions/TJ of input fuel energy) by the input fuel energy (TJ). The CO_2 emissions factors are provided from the IEA[44]. The distribution of emission factors for NOx, CO, SOx, and $PM_{2.5}$ are sourced primarily from the European Monitoring and Evaluation Program (EMEP) and the European Environment Agency (EEA) Air Pollution Emissions Inventory Guidebook[45]. The distribution represents the range of current combustion and abatement technologies in absence of specific operating characteristics for a country's generation mix and can be found in Tables A5-A7. Data on input fuel energy for power generation in SSA comes from the IEA[46]. Such data includes consumption of natural gas, bituminous coal, lignite coal, "gas/diesel", fuel oil, and crude oil used for power generation in each country. Furthermore, the IEA reports generation from low-carbon sources of electricity, including hydropower, solar, wind, biomass, and nuclear. We assume emission factors for electricity generated using these sources to be negligible. All emission factors, associated distributions, and related calculations and can be found in Tables A5-A9 in the Appendix.

The weighted emissions factor estimates the emissions associated with electricity generation across all sources. We calculate country-specific emissions factors by pollutant based on the breakdown of electricity generation and the respective emission factor using the following equation:

$$\boldsymbol{weighted\ \varepsilon_p = \sum_{i=1}^{n} x_i \varepsilon_{p,i}} \qquad (2.4)$$

Where x_i is the percentage of total generation by fuel type *i* (coal, natural gas, hydro, etc.), and $\boldsymbol{\varepsilon_{p,i}}$ is the effective emissions factor for pollutant p for fuel type i – as the given emission factor for each pollutant (in kg/TJ) multiplied by the fuel energy (TJ) and divided by the reported electricity generation – with units of kg/MWh. Figure A3 in the Appendix shows the installed capacity and generation of each country.

2.1.1 – Emissions from Diesel Backup Generators

Default diesel generator emission factors are used for CO_2, SOx, NOx, CO, and $PM_{2.5}$[39,47]. Table A8 in the Appendix lists the emissions factors of pollutants for diesel generators included in this analysis. We assume an upper bound operating heat rate of 10.3 MJ/kWh (35% efficiency)[39] and a lower bound of 20%. We choose our mode for the triangular distribution to be 25% following guidance from the United Nations Development Program[48]. We assume that this efficiency distribution accounts for partial loading, age of generator, and general wear and tear. Partial loading occurs when running diesel with generators at less than rated capacity and is known to gradually reduce operating efficiencies and cause increased emissions[49].

For this analysis, we assume that backup diesel generation replaces the electricity lost due to power outages over a triangular distribution of backup capacity available (measured as a percentage of total installed capacity in the grid). The capacity is bounded from a minimum of 1% to the maximum observed value in the respective African Union region. The values of the triangular distribution are identified from recent estimates in the literature[34].

2.1.2 – Inputs of diesel generator economic analysis

Reliance on backup diesel generators can increase the costs of electricity for users in SSA. For this analysis, we estimate the difference in the price of electricity from the central grid and the costs of self-generation with backup diesel generation. Diesel prices, obtained from the World Bank, vary widely across SSA[4]. We use country-specific diesel costs to estimate the costs of backup electricity, using a distribution of diesel generator efficiencies described above and diesel fuel heating value of 38.7 MJ/liter[50]. We similarly collected country-specific data on electricity prices. Tariff data represents averages across residential, industry, and commercial prices[51,52]. Our backup diesel generation costs are based only on fuel needed to provide electricity commensurate to that which would be lost in a power outage and can be found in Table A10 in the Appendix. We do not consider any capital costs or operation and maintenance costs for the diesel generators. While the distribution of diesel generator efficiency does not affect the price of fuel, efficiency does affect the amount of fuel consumption and thus it affects the total cost for providing diesel generation. All values for the economic analysis are in 2014 dollars. The results of the analyses described above are in the next section.

2.3 – Sustainability Impacts of Backup Diesel Generators

In this section we summarize the results of our MCA. We focus our discussion on the amount of electricity generated with backup diesel generators, the net change of fossil energy consumption from power generation, and the net change of air emissions.

2.3.1 – Emissions from Grid Electricity in sub-Saharan Africa

Figure 2.1 shows the mean weighted-average emission factors for grid electricity for the SSA countries in our analysis in 2014. This figure reports the mean from the MCA described in the methods section, which account for uncertainty in emissions factors for power plants with different efficiencies and pollution control technologies. Weighted-average emission factors for Carbon Monoxide are presented in Figure A1, and the full distributions for these results are available in Table A1 in the Appendix. The method we used for estimating emissions from power plants (see Methods) is in line with best practices[45] and has been used in recent emission estimates[53,54].

The emissions factors reported in Figure 2.1 can be used to compare the current state of a country's generation mix and efficiency to others across the continent. The maps indicate intensity of emissions factors with yellow representing relatively low emission factors (compared to other countries in the data set), and black indicating relatively high emission factors. Countries in white were not included in this analysis due to lack of consistent data (or they are not part of sub-Saharan Africa). The results show the countries with the largest mean weighted-average emissions factors – in parentheses – include Niger (1,050 kg CO_2/MWh; 17 kg SOx/MWh), Senegal (0.29 $PM_{2.5}$ kg/MWh), South Africa (4.6 kg NOx /MWh), and Nigeria (0.33 kg CO/MWh). The lowest emissions factor for all pollutants are found in the Democratic Republic of Congo, Mozambique, and Ethiopia. These countries have negligible air emissions from power generation as they rely on hydropower for more than 90% of their grid electricity.

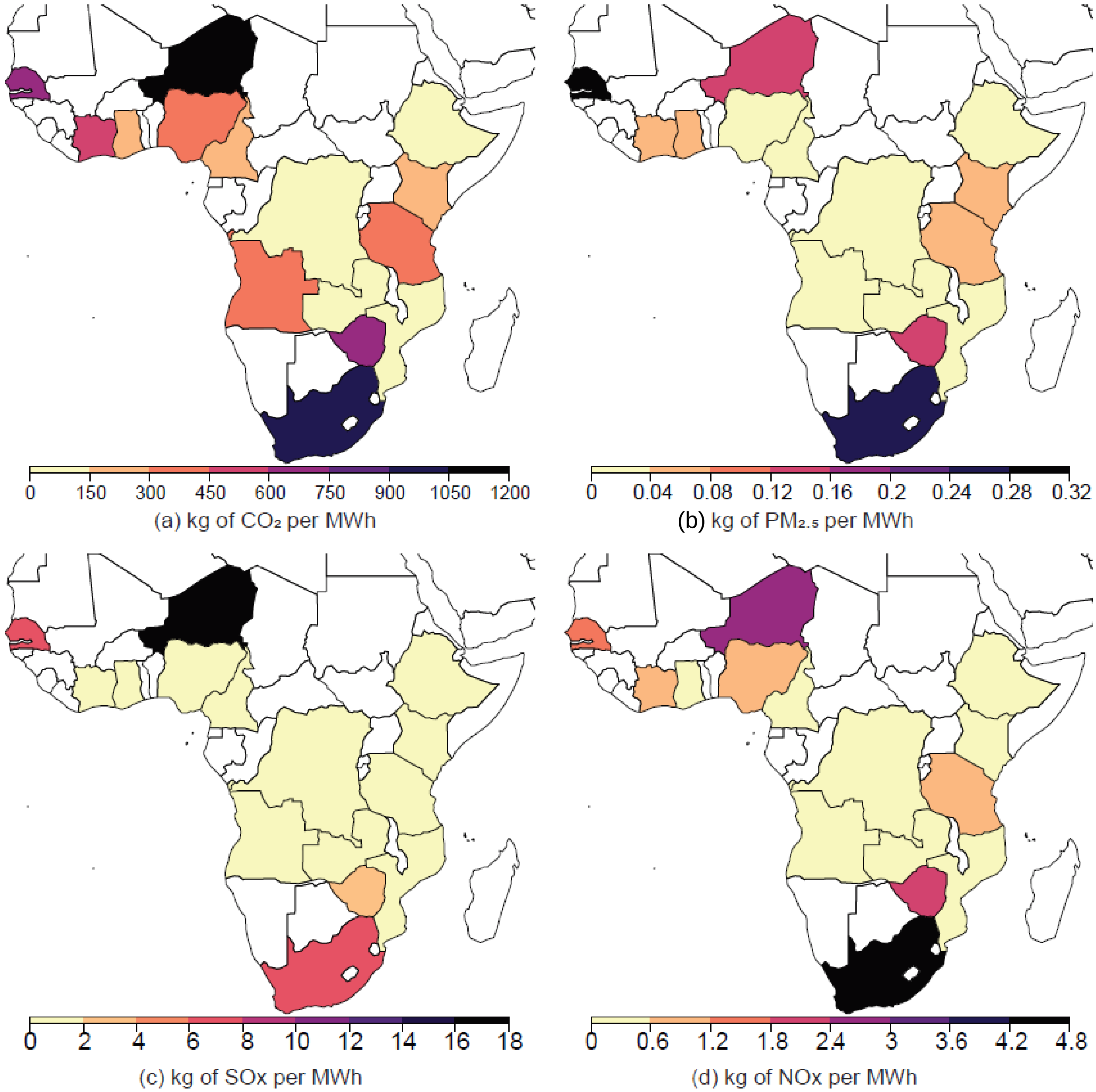

Figure 2.1: Mean Weighted-Average Emissions Factors for Grid Electricity by Country in 2014. Darker shades indicate greater relative emission intensity. Note that scale changes for each pollution map. Countries shown in white were not included in the analysis.

2.3.2 – Backup Electricity

The amount of generation lost and subsequently replaced by backup generation is a key contributor to emissions and costs. Figure 2.2a shows the distributions of results from our MCA. These results are driven by the capacity of diesel backup available in each country and the annual outage hours experienced (from Table 2.1). The ridgeline plots in Figure 2.2 represent 90th percentile confidence interval from the MCA. Median values in Figure 2.2 are identified by black lines in the plots whereas peaks represent the highest frequency of data points observed. Countries that display relatively flat plateaus with no peak are indicative of a larger range of outputs and thus more uncertainty.

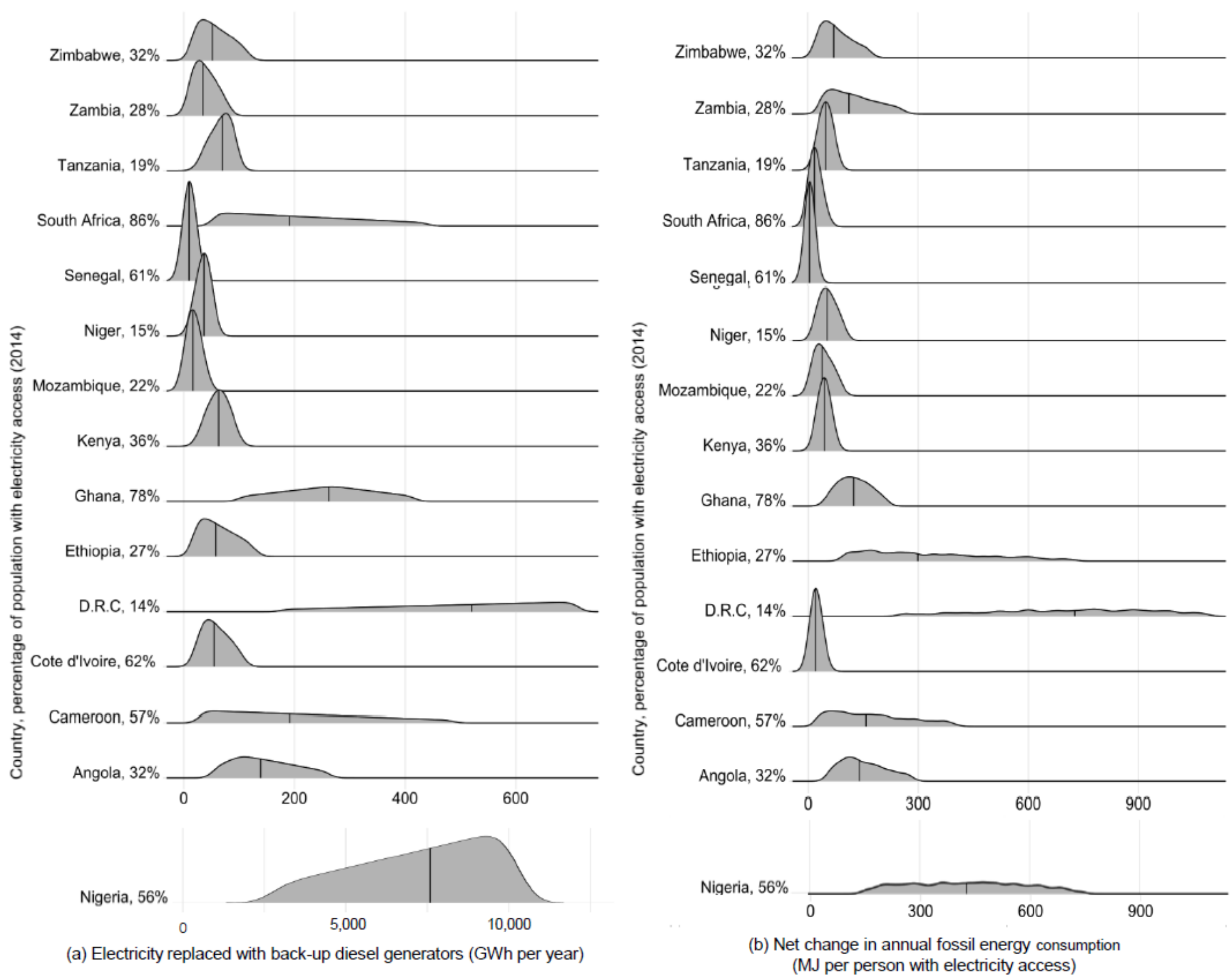

Figure 2.2: Backup electricity generation and annual change in fossil-fuel consumption. Ridgeline plots of (a) electricity provided by backup generators and (b) the net change in fossil fuel energy consumption as a result of backup generators replacing grid-based electricity. The country labels include the percentage of each country's population that has access to electricity (2014 values). The distributions of each country reflect the 90th percentile confidence interval of outputs observed from our Monte Carlo Analysis with

the y-axis indicating frequency of observance. Median values in each country are represented by black lines. Nigeria is shown separately as the output range for electricity generated is an order of magnitude greater than in other countries. Note that the scale of the x-axis differs in each panel.

Nigeria, which experiences outages for more than half the hours available in a year, generates about 7 Terawatt-hours of electricity annually with backup generators. This is equivalent to nearly 25% of their grid-based generation. South Africa, which experiences the lowest outage levels in the countries analyzed and has a relatively low percentage of backup capacity, nonetheless generates as much electricity from diesel generators (mean generation of about 200 GWh) as some countries with higher outage levels and larger percentage of capacity from backup generators (like the D.R.C and Niger). This result is driven by the significantly higher capacity of the grid in South Africa (installed grid capacity ~46 GW) compared to other countries (the installed grid capacity of the D.R.C is ~2.6 GW and 0.18 GW in Niger).

2.3.3 – Fossil Energy Consumption

As part of SDG 7, the UN calls for significantly increasing the share of renewable energy by 2030. Because reliance on backup diesel generators increases the contribution of fossil fuels to a country's energy mix, tracking the net change in fossil energy consumption for power generation can serve as a metric for tracking success with SDG 7.3 We estimate the difference in annual fossil fuel energy consumption for electricity generation within a country's existing grid compared with electricity generated from backup diesel generators during outages, as shown in Figure 2.2. The values in Figure 2.2b are normalized by population that has access to electricity in each country in order to allow a comparison across countries of different population sizes. This comparison assumes that without outages the power grid would provide electricity with the same mix of generating resources currently available in each country. In reality, if a specific power plant caused the outage, the emissions changes would be relative to that plant's characteristics. Furthermore, the time of the day when the outage occurs may also have implications for the emissions displaced. Unfortunately, without detailed data on the cause and exact timing of the outages, a more detailed analysis is not possible at this time.

Replacing electricity generation lost during power outages with backup diesel generation increases fossil energy consumption, even in countries that are heavily reliant on fossil fuels like coal and oil for their grid electricity. Countries most reliant on fossil electricity generation see fossil energy consumption increase by 50% when using diesel backup. In countries with little to no grid-based fossil generation, diesel backup can lead to increased fossil energy consumption 1,000 times that of the grid. Backup diesel generators are typically more inefficient than centralized power plants, thus driving these results. Although the characteristics of backup generators may differ across countries, we do not have sufficient data to account for such differences. This limitation notwithstanding, the results indicate that using diesel generators for backup power could continue to limit these countries' ability to decrease the share of energy provided by fossil fuels, even as they expand renewable energy capacity to reach new electricity customers.

2.3.4 – Air Pollutant Emissions

Figure 2.3 shows the net changes in annual emissions of CO_2, $PM_{2.5}$, SOx, and NOx that result from replacing grid electricity with backup diesel generators during power outages. We highlight the results for these pollutants as they are the most important for climate and human health. The results for carbon monoxide are available in Figure A2. As before, these results are normalized by the population with access in each country. This comparison also assumes that, without outages, the power grid would provide electricity with the same mix of generating resources currently available in each country.

Figure 2. shows that Niger has negative net median annual CO_2 emissions while South Africa has a high proportion of negative values within the 90^{th} percentile confidence interval. These countries heavily rely on coal for their grid electricity. Several countries also have negative values of SOx emissions in Figure 2.b, which are driven primarily by uncertainty in SOx emissions factors from the power plants in the central grid. At the tail of the distribution for the emissions factors for heavy and light oil used in centrailized power plants (representing little pollution control), SOx emissions from the grid outpace

those of diesel generators. Nonetheless, negative values shown in Figure 2.3 only occur when the efficiency of backup generators approaches 35%.

The mean increase in annual CO_2 emissions in Nigeria is about 40 kg per person with access to electricity, however, Nigeria has the largest population with electricity access of the countries analyzed. Their high number of outages and backup generator capacity results in much higher changes in the magnitude of annual emissions than in other countries. Table A2 in the Appendix includes the magnitude of net emissions from backup generators for each country. The use of diesel-based backup generators in all countries result in net increases of mean annual air emissions among at least three of the five pollutants examined. While our work does not directly attempt to assess the health impacts of diesel generator emissions, as such an analysis would require a complete inventory of all emissions sources linked to chemical transport models and dose response models specific to the continent, we take the necessary first step of identifying the magnitude of emissions arising from generator usage during power outages. As better air quality data and models become available for SSA, the results of this paper could be translated to mortality and morbidity effects.

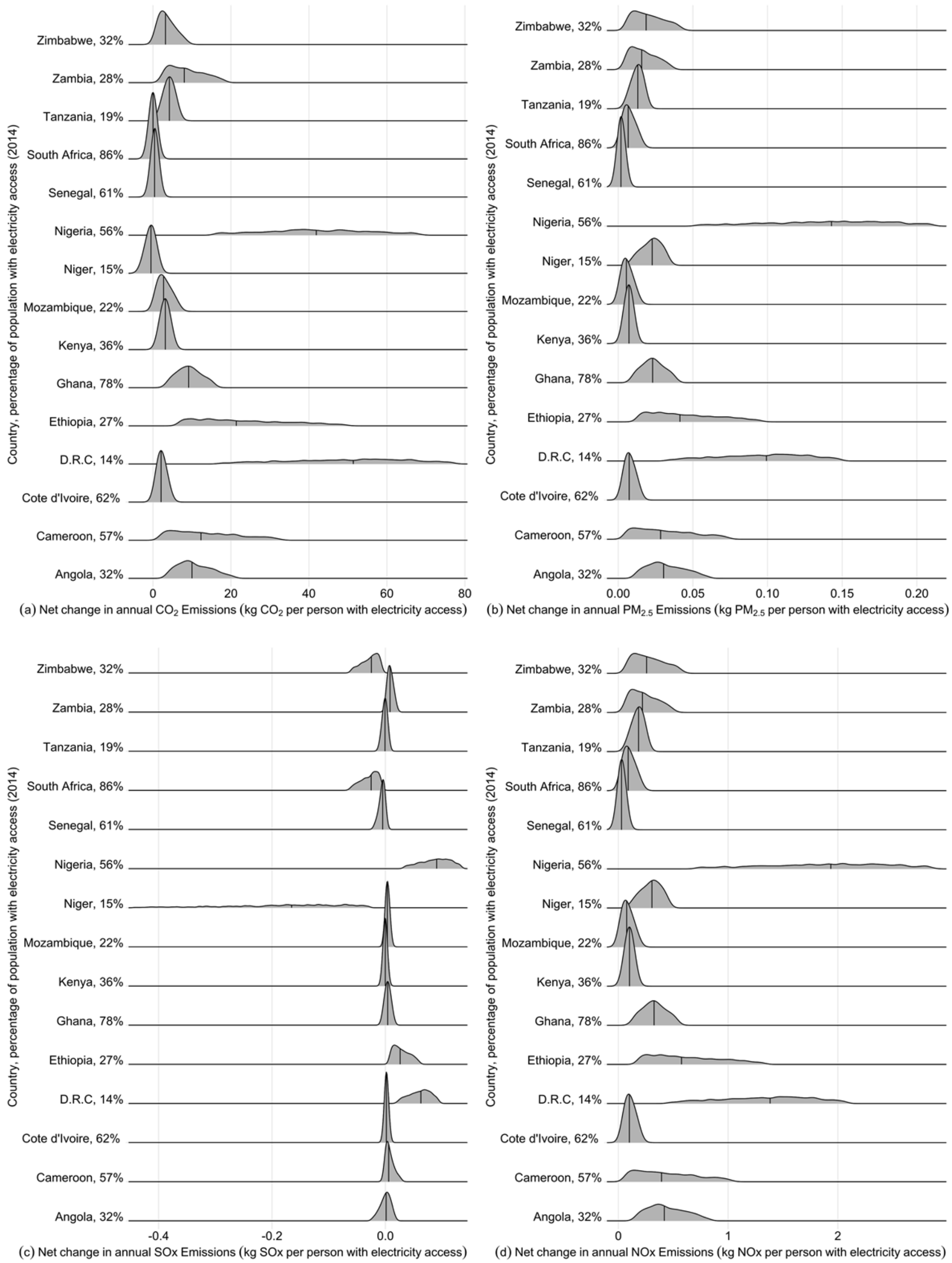

Figure 2.3: Change in annual emissions due to backup generation. Ridgeline plots of normalized impact backup diesel generators replacing grid-based electricity. The country labels include the percentage of each country's population that has access to electricity (2014 values). The distributions of each country reflect the 90th percentile confidence interval of outputs observed from our Monte Carlo Analysis with the y-axis

indicating frequency of observance. Median values in each country are represented by black lines. Note that the scale of the x-axis differs in each panel.

Even as countries in SSA expand low-emissions generating capacity, diesel-based backup generators used during power outages could continue to be a significant contributor to emissions of CO2 and other air pollutants. The results highlight potential emissions impact of improving access while ignoring reliability. For instance, if grid electricity access in the D.R.C (population of 73 million) is expanded form the current 13.5% to 50% while grid reliability remains at low current levels, (such that the normalized emissions intensity remains at the values reported in Fig. 2.3), the additional emissions from backup generators that support new connections could add about 1.3 million metric tons of CO_2 per year. Thus, improved power system reliability needs to accompany capacity expansion and increased connectivity in SSA to reach SDG 7 and SDG goal 3.9. In addition, at least 12 of the 15 countries studied have provided National Determinations of Contribution (NDC) for the Paris Agreement identifying goals of reducing greenhouse gas emissions[55]. Ghana's NDC, for example, outlines plans to reduce greenhouse gas emissions from the business as usual projections by as much as 45%[55]. Improving grid reliability for customers already connected to the grid would significantly aid in such reductions.

2.3.5 – The financial burden of unreliability

The use of diesel for backup electricity during power outages also has cost implications for consumers of electricity. Figure 2.4 illustrates the direct cost burden placed on consumers due to power outages using electricity and diesel prices in SSA countries in 2014. The cost differential, calculated as the difference in the cost of generating electricity in a diesel backup generator and the price of grid electricity, is driven by the price of diesel in each country, generator efficiency, and the price of grid electricity. We find that consumers in Zambia incur the largest cost premium, at US$0.53/kWh. In 2014, diesel fuel prices in Zambia were US$1.59 per liter, resulting in a mean generation fuel cost (excluding capital, operation, and maintenance) of US$0.59/kWh, while the price of grid electricity was only US$0.06/kWh. The DRC and Zimbabwe have the second and third highest cost premium (about US$0.49 and US$0.45 per kWh, respectively) while Angola has the lowest cost premium (US$0.13/kWh). All countries see an increase in electricity costs when replacing electricity from the grid with diesel backup. Note, however, that this analysis does not capture capital costs nor maintenance costs of generator systems indicating that the true cost premium may be even higher, in addition to the monetized damages to human health that are not included.

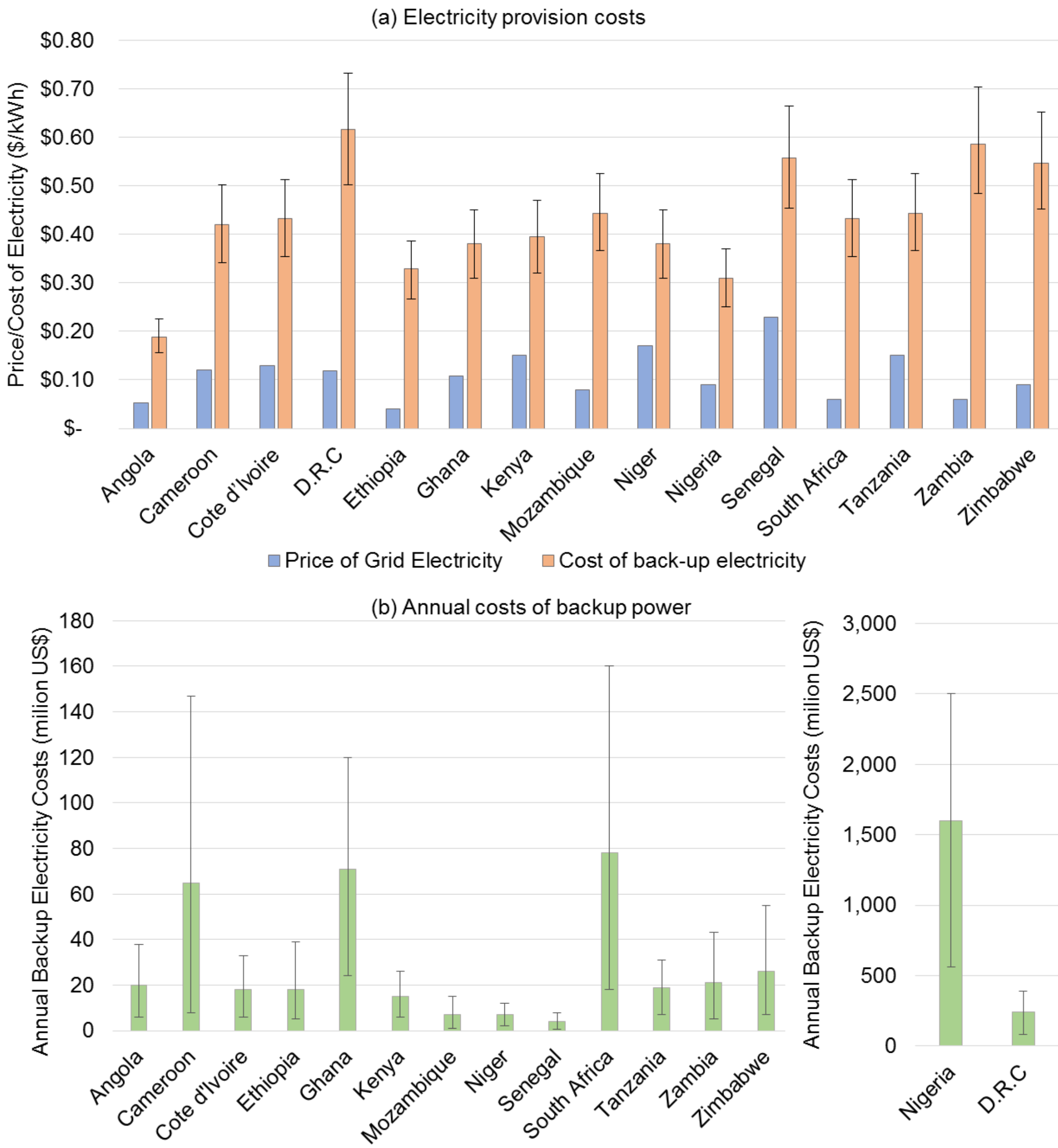

Figure 2.4: Cost of backup power. (a) Blue bars represent grid electricity prices (US$/kWh) and orange bars represent the cost of backup electricity (US$/kWh) (2014 values). (b) Annual costs consumers incur for backup power. Uncertainty bars reflect the distribution of diesel generator efficiencies and amount of load replaced by backup generators, which are the main drivers of fuel consumption.

Figure 2.4b shows net electric cost for all countries within the 90th percentile of the output distribution from our MCA. The figure highlights the costs associated with annual load lost and replaced during power outages based on the distribution of backup capacity multiplied by the average hours of outage in a year in each country (see Equation 2.1 in the Methods section). Although generation efficiency factors into the final costs, the load replaced by diesel generators is the major driver of uncertainty in the MCA. Nigeria, with its high frequency of blackouts, has a mean net cost of electricity from diesel generators of around $1.6 billion per year while Senegal has a mean net cost of about $4 million per year. We use average electricity prices across the residential, industrial, and commercial sectors yet residential electricity is typically more expensive than the latter sectors. Considering most backup generation is used in industry and services[14], the true cost premium associated with reliance on backup generators is likely higher than our estimate, and that rising diesel costs would increase the cost premiums.

It is worth noting that these direct costs to consumers and do not account for benefits of maitaining electricity supply during outages (which include, for example, avoided product loses). Similarly, electricity tariffs are often subsidized in SSA, so the cost consumers face may not reflect the true cost of grid electricity. Nonetheless, the analysis of the costs we present in this paper indicate that the direct costs of relying in back-up generators is inconsistent with SDG 7.

2.4 – Discussion

In this chapter we analyze the energy, emissions, and consumer costs of power outages in sub-Saharan African countries. By modeling the fuel mix for the central electricity grid in each country and the diesel fuel needed to produce backup electricity during outages, we estimate the magnitude of these impacts in the region. We show that use of backup generators leads to higher fossil energy consumption (compared to the central grid) in all countries, even countries that already rely on fossil fuels for power generation at centralized plants. Furthermore, for all countries in the analysis, backup diesel generators result in increased mean emissions of at least three of the five pollutants analyzed, compared to the grid. While the results in the previous sections were normalized for comparison, it's important to contextualize the magnitude of the changes emissions. In several countries, particularly those reliant on non-fossil electricity generation, emissions from backup power during outages can exceed annual grid-level emissions. In the predominately hydropower-based D.R.C, for instance, diesel backup generation produces 55 times the amount of CO_2 and nearly 9,000 times the level of $PM_{2.5}$ of the grid. Backup generation in Nigeria produces CO_2 emissions equivalent to 60% of its annual electric sector emissions. The effects of backup diesel generators extend to countries with the least outage hours like Mozambique, where outages produce CO_2, $PM_{2.5}$ and SOx emissions equivalent to 3%, 300%, and 600% of its annual electric sector emissions, respectively. Table A3 in the Appendix summarizes annual emissions from the grid and the backup generators for each pollutant in each country. This level of potential emissions occurring mostly in population centers may lead to significant decreases in air quality, hindering progress toward reducing mortality and morbidity, as targeted in SDG 3.9. Finally, we show that the costs of electricity from backup diesel generation during outages can result in millions of excess consumer expenditures across the SSA region.

Our analysis highlights the magnitude of potential avoided emissions and economic savings from increased grid reliability, and has implications for achieving Sustainable Development Goals. Increased reliability may not lead to decreases in generator ownership[18], but it is likely to lead to decreases in generator use, thus avoiding additional emissions and reducing costs for consumers.

As noted previously, our analysis does not include an assessment of impacts of air emissions on human health, as estimating these impacts would require a complete emissions inventory, an air quality model, and exposure information. Similarly, we do not include all the costs and benefits of backup power (we only account for direct fuel costs). However, our analysis suggests that increasing the reliability of the current system can result in reductions of air emissions and fuel costs even without accounting for expansion in low-carbon electricity capacity. We thus suggest that investments in reliability of the existing grid (and ensuring reliability for new connections) should be part of the plans for achieving the Sustainable Development Goals in SSA countries.

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Chapter 3: Motorcycle-taxi Fleet electrification in Kigali, Rwanda

In this chapter we examine the feasibility of electrifying the motorcycle-taxi fleet in Kigali, Rwanda as a means of reducing emissions of criteria air pollutants to meet local and international air pollution goals. While this analysis is specific to Rwanda, the context is generalizable as many developing nations use motorcycles for transportation and have growing air quality problems. Of the major sectors contributing to air pollution and climate change, the transportation sector is expected to grow the fastest[56]. As the economies in SSA grow, their transportation sectors will also grow, thus driving growth in fossil fuel (gasoline and diesel) consumption to power transport. Here we seek to answer three key questions:

- How do tailpipe emissions from conventional motorcycles compare with power plant combustion emissions associated with electric motorcycles in Kigali, Rwanda?
- What are the health impacts associated with emissions from conventional motorcycles compared to those of electric motorcycles?
- What are the non-infrastructure costs associated with motorcycle fleet electrification?

3.1 – Introduction

Global passenger vehicle transport currently accounts for about 14% of greenhouse gas emissions[11]. While developed countries account for the vast majority of transportation emissions, developing countries' transportation emissions will rise as passenger vehicle ownership increases[11]. In sub-Saharan Africa (SSA), gasoline-powered motorcycles represent a considerable share of passenger vehicle growth and also provide formal and informal taxi services[12,13]. The simultaneous expansion of the electricity and transport sector in SSA offers an opportunity for technology leapfrogging and electrification of historically fossil-fuel powered transport. In the near-term, electrification of motorcycle transport could provide a path for reductions in greenhouse gas (GHG) emissions, air pollutant emissions, deleterious effects on health caused by air pollution, and fossil fuel use in SSA – all of which align with achieving the United Nations'

Sustainable Development Goals 3, 7, and 11[6]. In this chapter, we evaluate the economic competitiveness of replacing conventional gasoline motorcycles with electric motorcycles, assess the change in emissions and fossil energy consumption between the two alternatives, and calculate reductions in human health impacts.

In Rwanda, more than 80% of the vehicles registered since 2006 are gasoline-powered motorcycles[57]. Despite concerns of safety – approximately 15% of road crashes in 2013 were attributed to motorcycle crashes accounting for 32.8% of all serious (fatal and critical) road injuries[58] – motorcycles remain an integral part of everyday travel in the country's capital city of Kigali. Like many other cities in SSA, residents also derive income from driving motorcycles as commercial taxis or "motos"[12,13]. In Kigali, home to over one million people, approximately 30,000 motos constitute 21% of all passenger trips (motorized and non-motorized)[13,59]. The ubiquitous nature of moto trips, despite concerns of safety, indicate they are likely to remain a major source of transportation for the foreseeable future.

Rwanda has also identified concerns with poor air quality, which contributed to 2,200 deaths (95% Confidence Interval 1,200-3,300)[60] in 2012. Acute respiratory infections accounted for 21.7% of health center admittances and 6.8% of hospital admittances, and the infections are the largest cause of death in children under the age of 5[57]. These infections are associated with air pollution in the country[57]. The Rwandan Environmental Management Agency recently commissioned a study to identify and address air quality related to anthropogenic air pollution[57]. In the transportation sector, the study identifies the following pollutants as particular concerns: nitrogen oxides (NOx), particulate matter (PM_{10}, $PM_{2.5}$), carbon monoxide (CO), and hydrocarbons (HCs)[57]. Additionally, as a signatory to the Paris Agreement, Rwanda has signaled its desire to contribute to the overall fight against climate change and has developed its Nationally Determined Contribution (NDC)[61]. Their NDC focuses on greenhouse gas reduction efforts across the energy, transportation, industrial, waste, and forestry sectors. More specifically, GHG reduction efforts within the transportation sector focus on opportunities in public transportation, infrastructure, and regulatory bodies. While increased regulation of tailpipe emissions could also lead to reductions in GHGs, the NDC does not explicitly identify opportunities for tailpipe GHG reductions despite acknowledging an expected 20% increase in light-duty vehicle ownership by 2030[61].

While motorcycles are known to have greater fuel economy than gasoline-powered passenger vehicles, there are tradeoffs in the form of additional air pollutants[62,63]. Comparisons of passenger cars and motorcycles found that, although motorcycles emit less carbon dioxide (CO_2) than cars, motorcycles emit more hydrocarbons (HC), carbon monoxide (CO), and nitrogen oxides (NOx) per kilometer[62,63]. Air pollutants from both motorcycles and passenger vehicle tailpipes can result in significant health impacts to the surrounding populations, especially in dense urban areas[64–66]. In developing nations, researchers have been examining electric motorcycles as a means to reduce emissions from conventional motorcycles that constitute a significant portion of their total VMT[67–70]. Two studies, Cherry et al. (2009) and Ji et al. (2012), compared the characteristics of electric vehicles (cars and scooters/bikes) with those of conventional vehicles (cars, buses, or motorcycles)[69,71]. These papers focused on China's use of electric scooters and bicycles. Given China's reliance on coal for power generation, Cherry et al. (2009) and Ji et al. (2012) found that electric scooters/bikes provide limited emissions reductions compared to conventional motorcycles. Cherry et al. (2009) used a life cycle assessment framework and found that emissions associated with lead-acid batteries used at that time also contribute to the emissions from electric scooters and bicycles [69,72–74]. In their work, did not include motorcycles. Nor did they evaluate the economic viability of electric scooters and bicycles as replacement for conventional models. Finally, newer electric motorcycles use lithium-ion batteries, which may be more environmentally friendly that lead acid batteries. Our work aims to make a contribution by assessing the deployment of electric motorcycles with lithium-ion batteries. Furthermore, we extend the comparative analysis to include conditions found in sub-Saharan Africa. Specifically, we consider the prevalence of taxi-motorcycles as opposed to scooters or bikes and account for an electricity generation mix with less fossil fuel dependence. For the health risk analysis, we build upon the work of Ji et al. (2012).

In this chapter we describe a comparison of motorcycle emissions, emission-associated health risks, and ownership costs between a conventional motorcycle and three models of electric motorcycles in the context of Kigali, Rwanda. First, we provide a first-order estimate of emissions associated with gasoline motorcycles and electric motorcycle alternatives based on extrapolated driving demand data for moto taxis in Kigali. Second, we estimate the change in health risks resulting from the fuel switching inherent to replacing conventional motorcycles with electric motorcycles. Finally, we assess the economic competitiveness of electric motorcycles in the context of a sub-Saharan Africa city.

3.2 – Methods

In this section, we provide a detailed account of the inputs, models, and analysis conducted for this chapter.

3.2.1 – Driving Data

We use trip data from a commercial motorcycle ride sharing platform, SafeMoto, in Kigali, Rwanda as the basis of this analysis[75,76]. The dataset consists of fleet-level data collected via GPS tracking of 118 drivers over a 30-day period (October 24 through November 23). The tracking took place towards the end of the long-dry season which runs from June through mid-September and overlaps with the short rain season (October to November)[77]. This time period should be relatively representative of the full year as it encompasses periods of low rainfall found during the long dry season while sampling days from slightly higher rainfall periods. The dataset includes the number of trips each driver conducted and the total distance each driver traveled during the 30 days. In total, the data account for of 31,000 trips and 240,000 km traveled. The average number of trips per driver over the period is 260 (Standard Deviation: 180) with an average of about 2,100 km travelled (SD: 1,500). This is an average of 8.6 km traveled per trip across all drivers (SD: 7.6). Figure 3.1 provides histograms detailing the distribution of trips and travel across the 118 drivers. This SafeMoto data provides a basis to estimate city-wide fleet (approximately 30,000 motorcycles as of 2018)[59] travel, which is necessary for modelling demand of an electrified fleet. Based on the SafeMoto data, we estimate one motorcycle travels about 25,000 km per year. As electrification efforts would occur gradually, we analyze electrification in 1,000 motorcycle increments (~25 million km per 1,000 motorcycles per year in the base case).

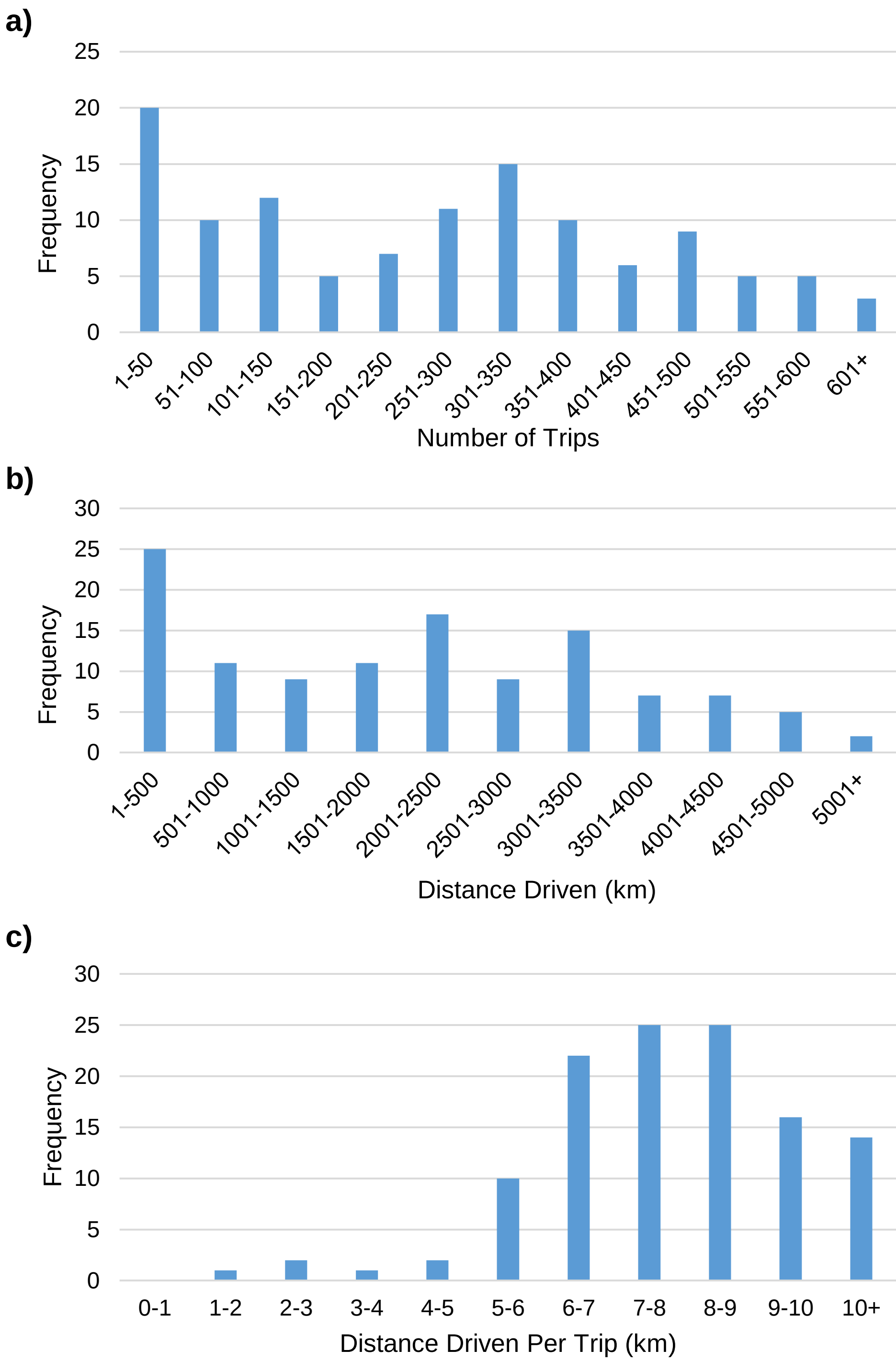


Figure 3.1: Histograms of trip characteristics. a) The number of trips SafeMoto drivers took in a 30-day period. b) The distance (in kilometers) SafeMoto drivers drove over the

30-day period. c) The average distance driven per trip for each driver. The total number of drivers in this sample is 118.

3.2.2 – Motorcycle Characteristics

This analysis explores transitioning the current fleet of gasoline powered motorcycles to either new, gasoline powered motorcycles or three electric motorcycles alternatives on a per 1,000 motorcycle basis. We model the gasoline motorcycle using the performance specifications of a TVS Victor[78], a common motorcycle in Kigali and the reported majority of SafeMoto motorcycles[76]. Registration data obtained from the Rwanda Revenue Authority indicates that over 70% of motorcycles registered from 2014 – 2017 are of the TVS brand[76]. In order to capture a range of relatively capable and affordable electric motorcycles, we model two Zero Motors e-motorcycles (Zero S 7.2, Zero FXS 3.6) [72,73] and a CSC City Slicker[74]. These motorcycles represent commercially-available electric motorcycles (the Zero brand motorcycles are sold internationally) and are all relatively low-priced compared to other existing electric motorcycles. Table 3.1 lists the characteristics of the selected motorcycles. Fuel efficiency values for the electric motorcycles are calculated as the usable capacity of the e-motorcycle's battery divided by the manufacturer reported combined city-highway range. Battery recharging is a critical enabling component of e-motorcycles, especially when motos must offer on-demand ride services. E-motorcycle (and electric scooter) batteries are physically small and can be designed to facilitate swapping depleted batteries for fully charged batteries[79,80]. We assume implementation of battery swapping via dedicated battery recharging stations as a means to keep e-motos available when their batteries are depleted. As all drivers will not exceed their battery's range during the day, only a portion of drivers will need to swap at some point during the day. While the additional batteries won't add additional electricity demand, swapping as a service could require a refueling fee to drivers which is included as a distribution in the levelized cost of driving analysis (detailed in section 3.2.5).

*Table 3.1: Characteristics of Motorcycles Analyzed. *Note: the City Slicker's useable battery capacity is estimated based on the rated capacity of the battery[72–74,78].*

Conventional Motorcycle Model	Price ($2018 USD)	Fuel capacity (L)	Reported fuel efficiency (km/L)	Curb weight (kg)	Max sustained speed (km/h)	
TVS Victor	$ 1,800	8	72	113	90	
Electric Motorcycle Model	**Price**	**Usable battery capacity (kWh)**	**Estimated fuel efficiency (km/kWh)**	**Curb weight (kg)**	**Max sustained speed (km/h)**	**Battery Technology**
Zero S 7.2	$ 11,000	6.3	12.4	142	129	Lithium ion
Zero FXS 3.6	$ 8,500	3.3	10.5	114	121	Lithium ion
City Slicker	$ 2,500	1.8	27.7	113	68	Lithium ion

3.2.3 – Electricity generation and emission estimates

Data from the Rwandan Utilities Regulatory Authority (RURA) details the monthly electricity generation from each power plant and fuel type in Rwanda for 2016[81]. The domestic electricity generation mix throughout Rwanda in 2016 (620 GWh) is 43.3% hydropower, 32.3% natural gas, 11.6% diesel fuel, 9.8% heavy fuel oil, 2.3% solar, and 0.9% peat. While the city of Kigali's generation capacity in 2016 consisted primarily of diesel and heavy fuel oil, our data shows a 43% decrease in generation from these sources from 2015 to 2016. Furthermore, on-site interviews with Rwanda Energy Group personnel in 2017 revealed plans to move away from diesel-based generation. Ideally, marginal emission factors would be used to determine emissions associated with electrification. Marginal emissions refer to the electric plant used to generate electricity to meet incremental demand, and marginal plants vary by time of day and season[82]. In lieu of having data for the marginal plant, we model emission using the country-wide average emissions factors. Additionally, we conduct two additional analysis (detailed in section 3.2.6) using only peat-based electricity generation and using an increased penetration of solar-based electricity generation. This set of emission factors covers a wide range of potential outcomes and results that hold across this range can be considered robust. This approach allows us to provide a first-order estimate of emissions while considering the impacts of marginal emissions and potential changes in the generation mix in Kigali given limited data.

Electricity generation that would be necessary to power the e-motorcycles varies by the fuel efficiency and is calculated as the total estimated annual travel demand divided by respective fuel efficiencies with a penalty for charging efficiency (assumed 9% loss) and transmission and distribution losses (triangular distribution with bounds of 15% and 23% and most likely value at 20%). In total, each kWh of demand for electric vehicles requires an average of 1.24 additional kWh (90% CI: 1.2 kWh – 1.3 kWh) Using the reported travel distances, the fuel efficiency of the motorcycle options, and the electricity generation data from RURA, we compare and contrast the total fossil fuel energy consumed for the gasoline and electric motorcycles.

Estimates of emissions from electricity generation are determined using distributions of emission factors for power plants (See Table 3.2)[45,65]. Distributions are used in a Monte Carlo Analysis (MCA), which allows us to account for uncertainty in emission factors associated with power plant emission abatement technologies and tailpipe emissions of motorcycles. The MCA represents the range of potential outcomes across air pollution emissions. Electric motorcycle emissions are calculated as detailed in Equation 3.1. Electricity demand from the motorcycles is multiplied by power plant emission factors for $PM_{2.5}$, CO, hydrocarbons (HC), and NO_x adapted from distributions in the European Monitoring & Emission Program and the European Environment Agency (EMEP/EEA) Emissions Inventory Guidebook[45]. Carbon dioxide emissions for power plants are taken from the U.S. Environmental Protection Agency's GHG inventory[44]. Table 3.2 lists the mean, low, and high values of the emission factors used to calculate emissions from the grid (modeled as a triangular distribution). While we estimate the amount of electricity necessary to power the electric motorcycles, we do not account for timing of charging that can affect emissions profiles. However, assuming battery replacement is the dominant means of charging, load can be shifted as desired via charging schedules.

Note that upstream emissions associated with fuel extraction, production, and transportation for both electric power fuels and refined petroleum products are outside the boundary of this analysis, and including these would likely improve the footprint of electricity fuels versus petroleum products for transportation.

This work is intended as a first order analysis to understand the potential implications of motorcycle electrification, and the impacts of timing and optimization of charging cycles should be examined in future work. Emissions for gasoline motorcycles are calculated using annualized kilometers driven in the SafeMoto fleet times the CO, HC, and NOx emission factors (g/km) adapted from Tsai et al. (2017) and $PM_{2.5}$ emissions factors adapted from Meszler (2007)[65,69,83]. Note that the emission factor for motorcycle tailpipe $PM_{2.5}$ are not provided by Meszler and point estimates are used in similar analysis[71,83]. Similarly, tailpipe emissions of SO_2 do not include distributions. SO_2 emission factors are calculated through stoichiometric conversion of the sulfur content in Rwandan gasoline(150 ppm)[84].

$$Emissions_i = \sum_j \left(w_j \times \eta_j \times EF_j\right) \times \frac{BatteryCapacity_i}{Range_i} \times Distance_i \qquad (3.1)$$

Where *i* denotes the electric motorcycle models and manufacturer reported battery capacity (kWh) and range (km), distance represents the extrapolated annual fleet distance (km), w represents the weight (percentage) of each generation type “j” used in the grid, *η* represents the heat rate of each plant type “j” in the grid (in GJ/kWh), and EF represents the emission factors for each plant type (in g/GJ of fuel input). Emission factors are provided in Table 3.2.

*Table 3.2: Mean emissions factors for gasoline combustion in motorcycles [g/km] and electricity generation by source [g/kWh] Values in parenthesis indicate the lower and upper values of the triangular distribution. *Note: The SO_2 factor for motorcycle tailpipe emissions is calculated based on the stoichiometric conversion of mass-based sulfur content (150 ppm).*

Pollutant	**Gasoline Motorcycle Tailpipe[65,83] (g/km)**	**Thermal Diesel[44,45] (g/kWh)**	**Heavy Fuel Oil[44,45] (g/kWh)**	**Natural Gas[44,45] (g/kWh)**	**Peat[44,45] (g/kWh)**
Share of generation by fuel (w_j)	n/a	11.6%	9.8%	32.2%	0.9%
$PM_{2.5}$	0.1 *(No distribution provided)*	0.01 (0.00–0.03)	0.21 (0.01–1.04)	0.01 (0.00-0.01)	0.19 (0.03-0.36)
CO	1.14 (0.37–1.91)	0.18 (0.04–0.75)	0.17 (0.10–0.24)	0.34 (0.16–0.54)	0.1 (0.07–0.67)
SO_2*	0.003	1.91 (0.39–4.05)	8.65 (3.47–15.45)	0.003 (0.001-0.003)	25.6 (9.76–45.1)
HC	0.57 (0.23–0.91)	0.01 (0.01–0.01)	0.03 (0.01–0.04)	0.02 (0.01–0.09)	0.02 (0.01–0.04)
NOx	0.26 (0.17–0.35)	0.72 (0.23–2.26)	1.6 (0.74–3.48)	0.77 (0.12–1.66)	2.71 (1.55–6.33)
CO_2	59.9 (58.5–61.3)	780	790	430	1,200

3.2.4 – Health Risks

Human health risks from air emissions are assessed using emission estimates from electricity production, gasoline combustion, and intake fractions (iFs) of primary and secondary $PM_{2.5}$ from each vehicle and reported as additional mortalities annually. An intake fraction estimates the portion of air pollutants a population is breathing [71,85–87]. A one-compartment static iF is calculated to determine the proportion of vehicle emissions the population inhales. The one-compartment model is applicable when modeling conservative gases (slow reacting emissions) such as primary $PM_{2.5}$ and assumes the air is well mixed[86,88,89]. In accordance with the known risks $PM_{2.5}$ poses to cardiovascular health, only health risks of primary and secondary $PM_{2.5}$ will be assessed in this work. Note that we use iFs for secondary $PM_{2.5}$ (derived from SO_2 and NOx) reported in Humbert et al (2011)[90]. This model has been identified as particularly useful in areas with little data, however, the assumptions of well-mixed air and no time dependency bias the estimates upwards[87]. Indeed, mobile measurements of PM_{10} from all sources in Kigali revealed time dependency as maximum deviation between morning and afternoon measurements of about 30%[91]. Despite the stated limitations, the one-compartment model is considered reliable for comparative analysis[71] and provides reasonably accurate estimates in limited data situations[86,87]. Equation 3.2 below lists the formula for one-compartment static iFs:

$$iF_{compartment} = \frac{BP}{uH\sqrt{A}} \qquad (3.2)$$

Where B represents the average breathing rate of the population, P represents the population in a given area, u represents the wind speed, H represents the atmospheric mixing height, and A represents the land area. The value uH represents the dilution rate and is calculated as the harmonic mean of wind speed times the atmospheric mixing height at each time step (1-hour time steps). Wind speed and atmospheric mixing height are provided by NASA's Global Modelling and Assimilation Office as measured in Kigali in 2017[92]. We assume that the additional electricity generated for the electric motorcycles is supplied with the country's generation mix and thus emissions factors are derived from the total generation mix, as opposed to the local generation mix.

We make the simplifying assumption that emissions from the electric grid occur in Kigali rather than at the location of the power plants across the country. In doing so, we hold the population, land area, and metrological values constant for emissions generated by conventional motorcycles and electric motorcycles. This has an important implications to our analysis: Intake fractions will be the same for conventional and electric motorcycle emissions causing the difference in emissions to drive the health impacts. In reality, emissions from each power plant would occur locally with a different population exposed to the emissions. However, because Kigali has a population density that is 3 to 5 times greater than the rest of the country[93], unless the dilution rate in other regions are 3 to 5 times greater than Kigali's our intake fractions may represent the upper bound.

Table 3.3: Modelling characteristics of intake fractions for the city of Kigali

Modeling Characteristic	**Value**
Breathing Rate (m^3/person-day)[90]	13.0
Population[93]	1,100,000
Dilution Rate (m^2/s)	344
Land Area (m^2)[93]	730,000,000
Mortality Rate (deaths per 1,000 people)[4]	6
$PM_{2.5}$ threshold (µg/m^3)[94]	10
Risk increase per 10 µg/m^3 of $PM_{2.5}$[94]	4%

In order to estimate the health risk (deaths/$kg_{inhaled}$), we calculate the linear no-threshold dose response as described in Ji et al (2012) using the health risk increase described in Pope et al. (2002). Equation 3.3 details the calculation.

$$HealthRisk = \frac{MortRate \times RiskIncrease}{B \times 365 days \times RiskThreshold} \qquad (3.3)$$

Where MortRate represents the 2016 mortality rate (deaths per 1,000 people) as reported by the World Bank[4], RiskIncrease represents the increased risk of death[94], B is the average breathing rate of the population, and the RiskThreshold is the linear emission elevation for primary and secondary $PM_{2.5}$. All values are provided in Table 3.3. This HealthRisk value is then multiplied by the emissions (kg) and the intake fraction (unitless) to determine the overall number of deaths attributable to each motorcycle.

3.2.5 – Levelized Cost of Driving

The driving demand combined with observed fuel and electricity prices in Rwanda allow us to estimate the costs of driving each of the motorcycles under consideration. In order to compare the total cost across the various motorcycle models we model the levelized cost of driving (LCD) for calculating cost per vehicle-kilometer-traveled (VKT) adapted from Elgowainy et al. (2018) (See Equation 3.4)[95]. We adapt a simplified version accounting for capital cost (with financing), vehicle lifetime, fuel consumption, and maintenance costs. For the electric motorcycles, we include the cost of battery swapping as a fuel cost which we assess as a fixed value for the cost of electricity plus a variable premium of up to 100% (over the cost of electricity) to account for the cost of the service. This is meant to be a proxy for the cost of refueling for the individual driver and may not reflect the true cost which would be set by the system owner or operator. While we are interested in fleet replacement, note that the LCD is a normalized metric that allows comparison across each motorcycle.

$$LCD = \frac{\frac{i(1+i)^n}{(1+i)^n-1} \times CapCost + Maintanence}{VKT} + \frac{FuelPrice \times ElectricModifier}{FuelEconomy} \qquad (3.4)$$

Where *i* is the discount rate of the Rwanda Central Bank (8%)[96] and n is the lifetime of the motorcycles (here, taken as 5 years in the base case). The ElectricModifier is a multiplying factor (uniform distribution with a minimum of 1 and maximum of 2) meant to act as a proxy for driver costs associated with swapping batteries. It is included in order to at least partially account for battery swapping at the point of service. LCD is reported in $2018.

Maintenance values for the conventional motorcycles are taken from reported average costs of maintenance in Kigali as provided by SafeMoto and are indicative of local servicing costs. Maintenance costs for electric motorcycles are estimates based on the costs of service for applicable components the conventional motorcycle but excluding the following components: oil change, chain alignment, oil filters, oil cable. The capital costs, aggregated maintenance costs, and fuel costs are presented in Table 3.4. A conversion rate of 830 Rwandan francs per US dollar is applied to all Rwandan costs.

Table 3.4: Values used in the economic analysis. All costs presented are in 2018$.

	Base Case			**Lower Capital Costs (electric only)**
	Capital Costs	**Annual Maintenance Costs**	**Fuel Costs**	
TVS Victor	$ 1,800	305 $/yr	1.30 $/L (1.10 – 1.60)	$ 1,800
Zero S	$ 11,000	150 $/yr	0.20 $/kWh (0.17 – 0.22)	$ 5,500
Zero FXS	$ 8,500	150 $/yr	0.20 $/kWh (0.17 – 0.22)	$ 4,250
City Slicker	$ 2,500	150 $/yr	0.20 $/kWh (0.17 – 0.22)	$ 1,250

Three additional economic scenarios are considered to account for cost changes and potential innovations in the space. The scenarios are as follows:

1) Lower capital costs of the electric motorcycles in consideration of future cost reductions – In this scenario, we assume capital costs of the Zero S is halved to $1,800 while the Zero FXS is decreased to $4,250 and the City Slicker is reduced to $1,250.
2) Increased lifetime of vehicles from 5 years to 10 years.
3) Both lower capital cost for the electric vehicles and increased lifetime considered.

3.2.6 – Sensitivity Analysis

In addition to the analysis presented above, we examine three cases that assess alternative electricity mixes and prioritization of high mileage drivers. First, we examine how marginal emissions and the introduction of more peat-based electricity generation would impact electrification efforts. In this case, we do not have data on the marginal plant used to generate electricity demand created by electrification but this role is typically filled by dispatchable fossil fuel plants[82,97]. Depending on the marginal generator, marginal emission factors can be significantly different than average emissions factors which would lead to an underestimation of emissions[97–99]. Rwanda has up to 155 million metric tons of peat reserves and has begun construction of an additional 80MW peat power plant which would alter the generation mix significantly[100–102]. As peat is one of the most polluting fossil fuels for power generation, we approximate the worst case impact of marginal emissions using all peat-based electricity[103]. We assess the new electricity generation from the 80MW plant over one year using a capacity factor of 0.53 as reported in Axelsson and Johnson (2017) with all other variables held constant[100]. We report the change in emissions observed for motorcycle electrification under peat-based electricity generation as well as the change in health impacts.

The second case examines how an expansion of solar power into the grid mix instead of peat would affect the electrification results. Here we revert back to average emission factors with the additional solar generation providing zero emission electricity. In this scenario, we add 370 GWh of solar which equates to approximately 220 MW of solar installed using a capacity factor of about 0.19. This solar capacity factor is back calculated from the observed electricity production (~14MWh in 2016) and the installed capacity of the Giga Watt solar photovoltaic field (8.5 MW)[81,104]. While the 220 MW addition would roughly double the 2016 installed capacity, the added generation falls well short of potential annual solar generation in Rwanda which is estimated to be over 65 TWhs[105]. Again, we report the change in emissions observed for motorcycle electrification under solar-based electricity generation and the change in health impacts.

The final case examines the impact of electrifying only the moto drivers who recorded the greatest mileage traveled over the observed 30-day period. These moto drivers fall in the upper quartile of drivers (n = 30) and have a total driving distance of about 74,000 km or 30% of the total distance driven. On average, the upper quartile of drivers covered an annualized distance of about 49,000 km (SD: 7,500 km). Recall that the mean annualized distance traveled for the entire SafeMoto fleet was about 25,000 km. As with the base case electrification analysis, we report the change in emissions (using average emission factors) and change in health impacts observed under this high mileage scenario for every 1,000 high mileage motorcycle driven.

3.3 – Results

3.3.1 – Emissions Comparison

Annual emission estimates from the conventional motorcycles and electric motorcycles for the five pollutants (CO_2, $PM_{2.5}$, SO2, NOx, CO, and HC) are provided here. These results indicate that across all pollutants, the TVS gasoline-powered motorcycle leads to more emissions of each pollutant than any of the electric motorcycle models. All discussion following refer to the mean values of the results derived using average emission factors. CO_2 emissions from conventional motorcycles exceed those of the Zero S, Zero FXS, and City Slicker e-motorcycles by 2.4, 2, and 5.2 times, respectively. This means that conventional motorcycles produce up to 5.2 times the CO_2 an electric motorcycle would cause the electric grid to generate over a year. $PM_{2.5}$ emissions, which plays a role in morbidity and mortality, are at least 40 times greater from conventional motorcycles than from the electric alternatives. These results are reported in Figure 3.2 with the bars representing the mean annual emissions and the error bars representing the 90% confidence intervals.

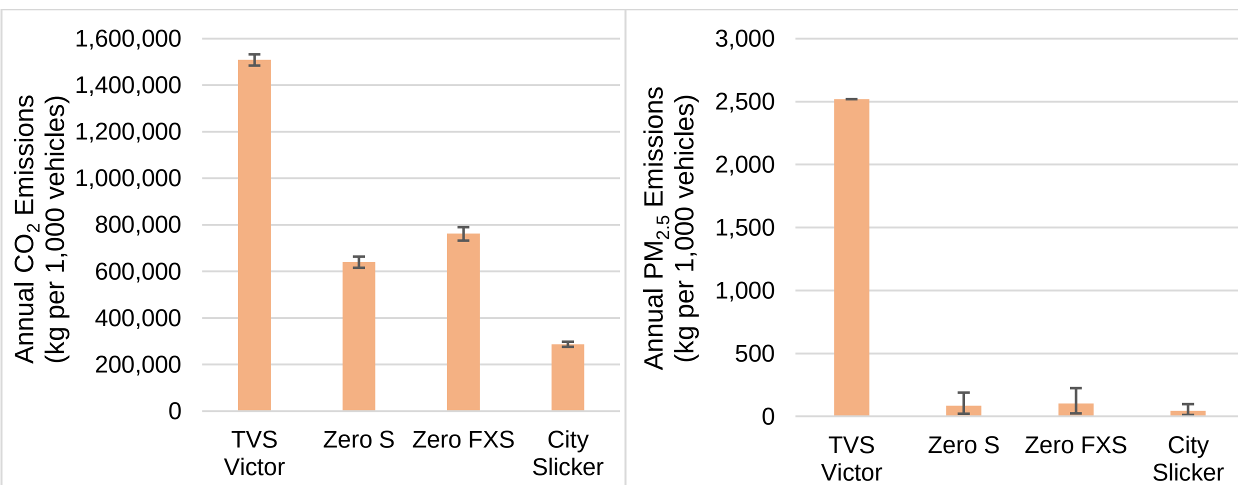


Figure 3.2: Estimates of mean emissions associated with conventional gasoline motorcycles and electric motorcycles. Error bars represent the 90% confidence intervals for each motorcycle and pollutant.

Mean emissions estimates of SO_2, NOx, CO, and HC are presented in Figure 3.3 illustrates the with their respective 90% confidence intervals. The greatest difference in emissions is observed in hydrocarbons where the conventional motorcycle emits from

560 to nearly 1,300 times that of the electric models. NO_x emissions from the TVS motorcycle are 6.7, 5.5, and 12.7 times greater than the Zero S, Zero FXS, and City Slicker, respectively. CO emissions from the TVS Victor are 85 to 190 times greater than our electric motorcycle estimates. Finally, SO_2 emissions from the TVS motorcycle were about 16 to 40 times less than those of the electric motorcycles. These findings are primarily driven by the displacement of fossil fuels when powering the electric motorcycles from the Rwandan grid which generates about 43% of its electricity from hydropower plants and 2% from solar sources. However, the relatively low sulfur content of gasoline in the conventional motorcycles leads to an increase in SO_2 emissions stemming from electricity generation of peat, heavy fuel oil, and thermal diesel. While the magnitude of emissions in the comparison would change based on the portion of fleet electrified, the analysis indicates that for every motorcycle electrified, non-SO_2 pollutants would at least halve current emissions.

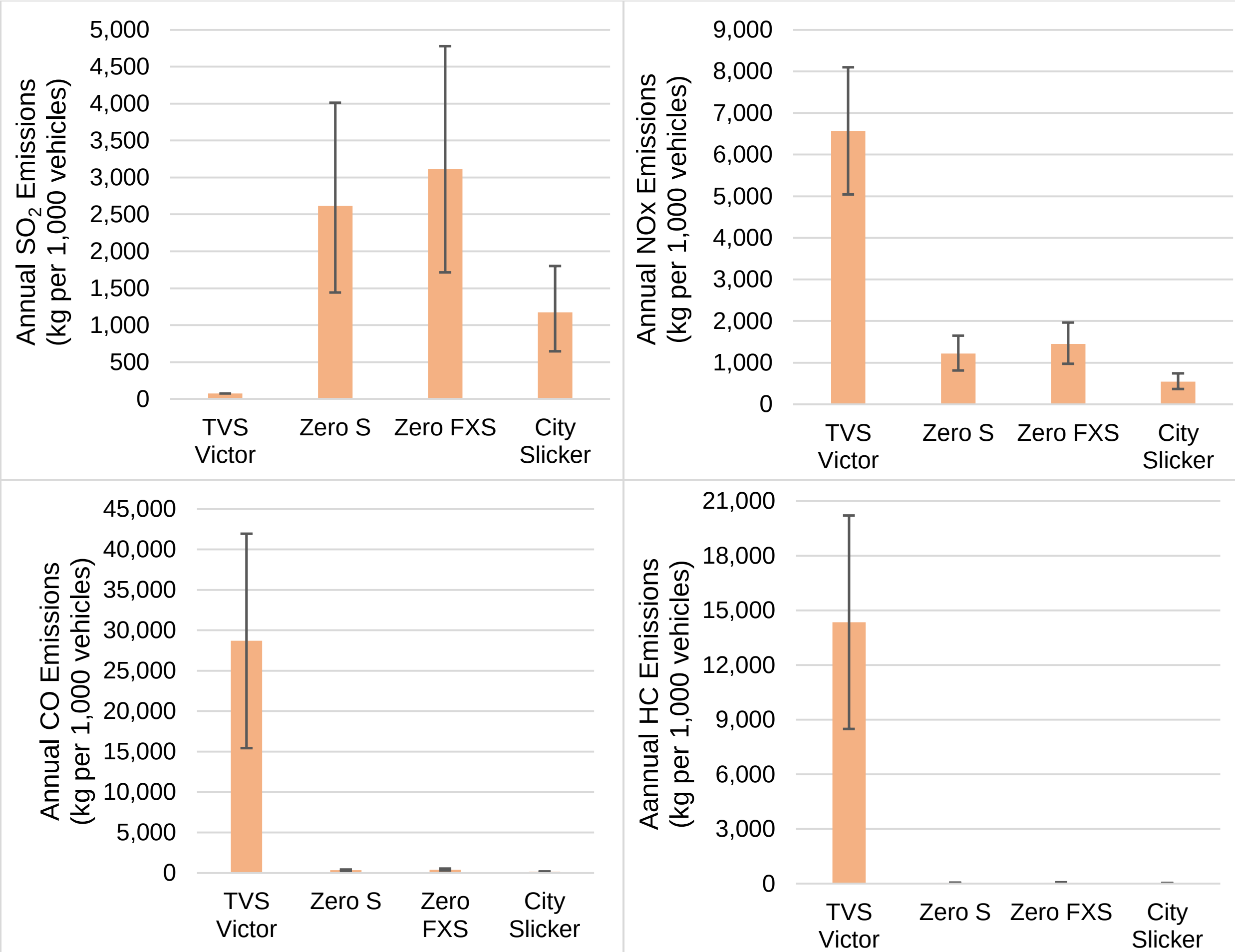


Figure 1.3: Estimates of mean emissions associated with conventional gasoline motorcycles and electric motorcycles. Error bars represent the 90% confidence intervals for each motorcycle and pollutant.

Uncertainty in the values are a result of uncertainty in the emission factors from the gasoline combustion in the TVS model, the power plants in the electric models, or the electricity losses sustained during transmission. The error bars indicate the 90th percentile confidence intervals and suggest that even if emissions from power plants are at the highest range (indicating no pollution controls or abatement) and the gasoline emissions were at their lowest range, the electric alternatives will produce significantly fewer emissions than a conventional motorcycle in all pollutants examined except SO_2. The emissions associated with e-motorcycles will continue to fall if the percentage of low-carbon generation in the Rwandan electricity grid continues to increase and the efficiency of transmission and distribution improves (See Section 3.3.4). The estimated displaced gasoline over the course of a year amounts to approximately 350,000 L per 1,000 electric motorcycles introduced while the increased electricity demand amounts to roughly 1-2 million kWh per 1,000 electric motorcycles introduced, or about 0.2% - 0.3% of the total grid electricity generation in Rwanda.

3.3.2 – Health Impacts

Our analysis indicates that for every additional kilogram of $PM_{2.5}$ inhaled annually, Kigali could see an increase of 5.06 deaths per year. This result primarily depends on the current mortality rate of the city (6 deaths per 1,000 people) and the toxicity of $PM_{2.5}$ (4% increase per 10µg/m^3) (See Equation 3.3). Note that an underlying assumption is the linearity and non-saturation of dose exposure from $PM_{2.5}$. Because we are interested in the change in deaths that can be associated with air pollution from conventional or electric powered motorcycles, we look at the associated deaths from conventional motorcycles as the base case. Any increases or decreases in this death rate associated with electrification is thus added or subtracted from the current death rate. As it takes significant amounts of $PM_{2.5}$ in the atmosphere to result in any attributable deaths, here we present the results of the entire motorcycle fleet's (30,000 vehicles) associated primary and secondary $PM_{2.5}$ related deaths. Recall that the average mileage used across the fleet is roughly 25,000 km. Figure 3.4 illustrates the results of this analysis.

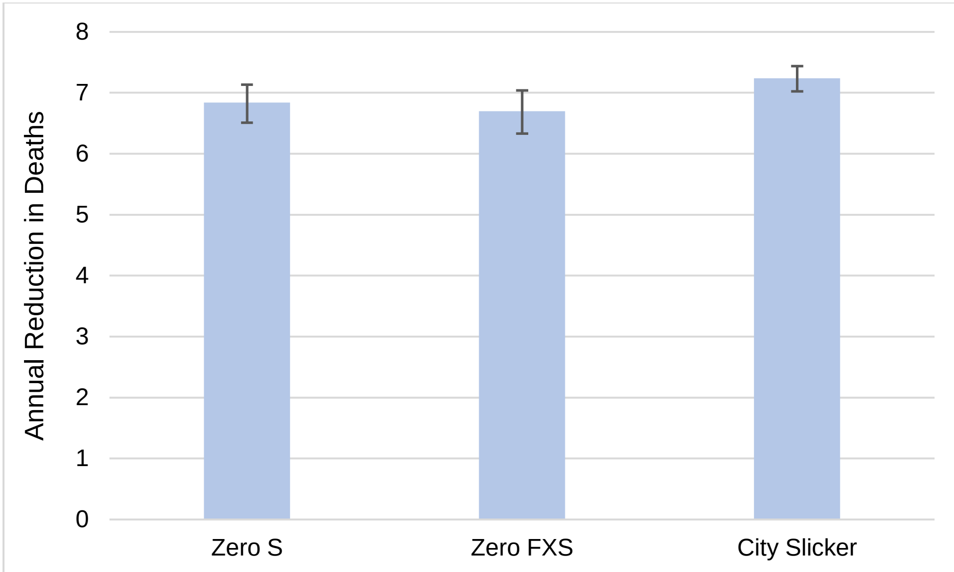


Figure 3.4: Reduction in death risk associated with motorcycle electrification. These values represent the annual reduction in deaths attributable to 30,000 electric motorcycles of each type replacing 30,000 conventional motorcycles driving an average of 25,000 km/yr. Error bars represent the 90% confidence intervals for each motorcycle.

The results show that the conventional motorcycles are responsible for about 7.6 deaths a year. When considering an electrified fleet, the emissions from electricity generation needed to power electric motorcycles equates to less than one deaths a year to 0.73. 0.87, and 0.33 for the Zero S, Zero FXS, and City Slicker, respectively. Reframing this analysis, we observe reductions in attributable deaths from motorcycle travel of roughly 7 each year. Our analysis shows that the majority of deaths from emissions associated with conventional and electric motorcycle use are caused by primary $PM_{2.5}$ and secondary $PM_{2.5}$, respectively. 90% of attributable deaths from conventional motorcycle emissions stem from primary $PM_{2.5}$ while about 34% of attributable deaths from electric motorcycles stem from primary $PM_{2.5}$. To put this in context, the total number of deaths associated with air pollution in Rwanda are approximately 2,200 (confidence interval: 1,200 – 3,300).

3.3.3 – Economic Results

Table 3.5 provides the normalized costs associated with each motorcycle for every kilometer driven. The LCD indicates that the TVS Victor is about 15% more expensive to own, operate, and maintain over 5 years than the CSC City Slicker despite the lower capital costs (roughly $900) of the TVS Victor. The two Zero brand motorcycles, have LCDs up to approximately 3 three times that of the TVS with the majority of that increase attributable to the initial costs of purchase. As we assume annualization of the purchase price of the motorcycles at the discount rates specified in the methods section, increasing the lifetime of the motorcycles does result in more competitive LCD from the Zero Brand motors. In fact, increasing the lifetime considered to 10 years results in a 15% decrease for the TVS and City Slicker, but a 25 to 30% decrease in costs for the Zero brand motorcycles. At 15 years, the Zero motorcycles see decreases of 30-40% while the TVS and City Slicker drop only 20% compared to the original scenario. Despite the reductions over time, however, the TVS and City Slicker are always the cheapest two options.

Table 3.5: Mean levelized cost of driving for a by motorcycle and scenario.

Vehicle	Base Case ($/km)	Low Capital Expenditures (Electric only) ($/km)	Longer Lifetime (n = 10) ($/km)	Low CapEx + Longer lifetime ($/km)
TVS Victor	0.05	n/a	0.04	0.04
Zero S	0.14	0.08	0.09	0.06
Zero FXS	0.12	0.08	0.08	0.06
CSC City Slicker	0.04	0.03	0.03	0.03

It's important to note that these LCD estimates may be influenced by the price of fuel, especially the electric models as we approach the battery swapping as a premium over the base price of electricity, and the transmission and distribution losses associated with electricity generation. Our analysis reveals that within a 25% change in fuel price (to both gasoline and electricity), the difference in LCD between the TVS and the City Slicker reaches a maximum of about one cent (with the City Slicker the cheaper of the two) at the extreme when gasoline increases by 25% and electricity prices decreases by 25% – the Zero brand motorcycle LCDs remain over 2 times the that of the TVS. When the scenario is reversed – gasoline prices decrease by 25% and electricity prices increase by 25% – the TVS becomes cheaper than the City Slicker by about half a cent through roughly 9 years of ownership. Within the examined ranges of fuel prices, the Zero brand motorcycles are never cheaper on a levelized basis than the TVS or City Slicker within reasonable timeframes (n <15 years).

3.3.4 – Sensitivity Analysis Results

The grid mix sensitivity analysis (Figure 3.5) reveals that marginal emissions generated with peat could significantly shift the emissions associated with an electrified fleet across several pollutants. Emissions of CO_2 associated with electrification of the Zero S and Zero FXS exceed those associated with the conventional motorcycle by roughly 50% to 80% under the marginal peat scenario. Across all electric motorcycles, emissions of CO_2 reach levels that are over 35 times those observed in the base case with weighted average emission factors. Although the City Slicker with its more efficient electricity consumption still produces about 2/3 the CO_2 of the conventional motorcycle. Similarly, results for NOx emissions show the Zero brand motorcycles exceeding those of the conventional motorcycle when peat is used as the marginal plant. Note that there is some overlap within the 90% confidence intervals indicating that the emissions are relatively similar.

Emissions of $PM_{2.5}$, CO, and HC see increases under the marginal peat scenario although these emissions still fall much lower than those generated from conventional motorcycles. SO_2 emissions show extreme growth under the marginal peat scenario. Whereas SO_2 emissions from electric motorcycles ranged from 16 to 40 times greater than those of conventional motorcycles in the base case, under the marginal peat scenario this range grows to a minimum of 300 times that of the conventional motorcycle (City Slicker) and a maximum of 820 times that of the conventional motorcycle (Zero FXS). On the other hand, when electricity for electric motorcycles is generated from a mix with increased solar power, emissions from electric motorcycles are reduced by 30% to 40% compared to those same emissions from electric motorcycles in the base case. This analysis reveals that if reducing emissions is a key policy goal, providing electricity using peat introduces additional tradeoffs in CO_2 and NOx emission increases while reducing the benefit of electric motorcycles among $PM_{2.5}$, CO, and HC.

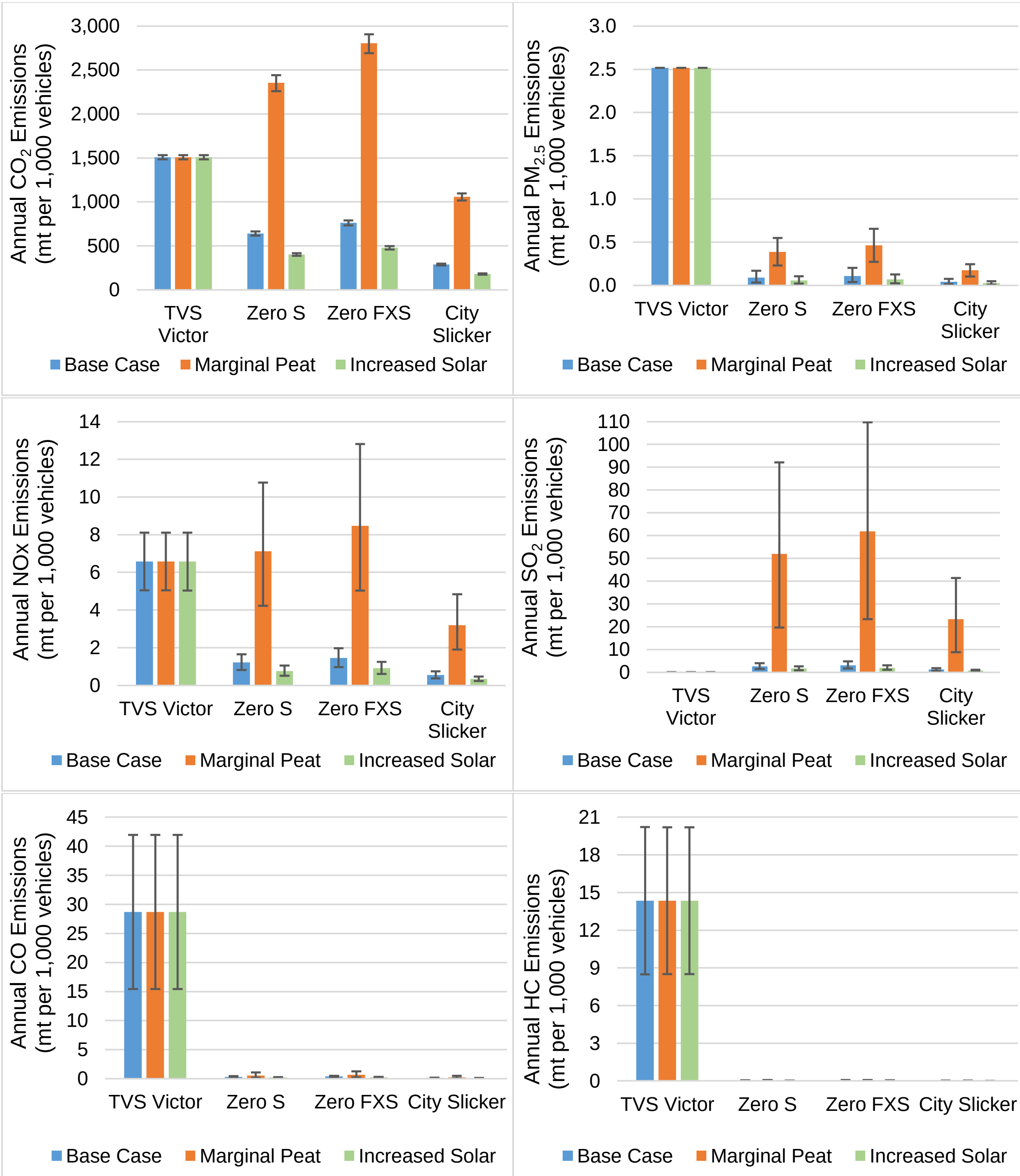


Figure 3.5: Estimates of mean emissions associated with conventional gasoline motorcycles and electric motorcycles by scenario. Error bars represent the 90% confidence intervals for each motorcycle and pollutant.

The health impact analysis indicates that reductions in annual deaths depend on the source of the electricity generation. Under the marginal peat scenario presented in Figure 3.6, mean results indicate that emissions attributable to the Zero brand electric motorcycles actually increase the number of deaths. This is due to the increase of Secondary $PM_{2.5}$ generated from SO_2 and NOx. While in the base case, roughly 65% of attributable deaths in electric motorcycles are caused by Secondary $PM_{2.5}$, in the marginal peat scenario, this value increases to 90%. However, within the 90% confidence interval we observe positive values which indicates that if emission factors in the peat plant are toward the low end (implying better emission abatement technology), even the all peat scenario could result in a reduction of deaths across all electric motorcycles examined. Results from the City Slicker electric motorcycle still indicate a reduction in deaths in the marginal peat scenario due to its increased fuel efficiency (leading to lesser electricity draw), although the reduction drops from about 7 lives saved to about 4 lives saved. In the increased solar scenario, there is some incremental increase to death reductions although the overlap in uncertainty implies these are not statistically significant. Intuitively, if all electricity generated for electric motorcycles comes from a dedicated zero emission source (such as solar) then electric motorcycles would eliminate all well-to-wheel emissions which in turn eliminates all emissions that would otherwise be generated with gasoline powered motorcycles.

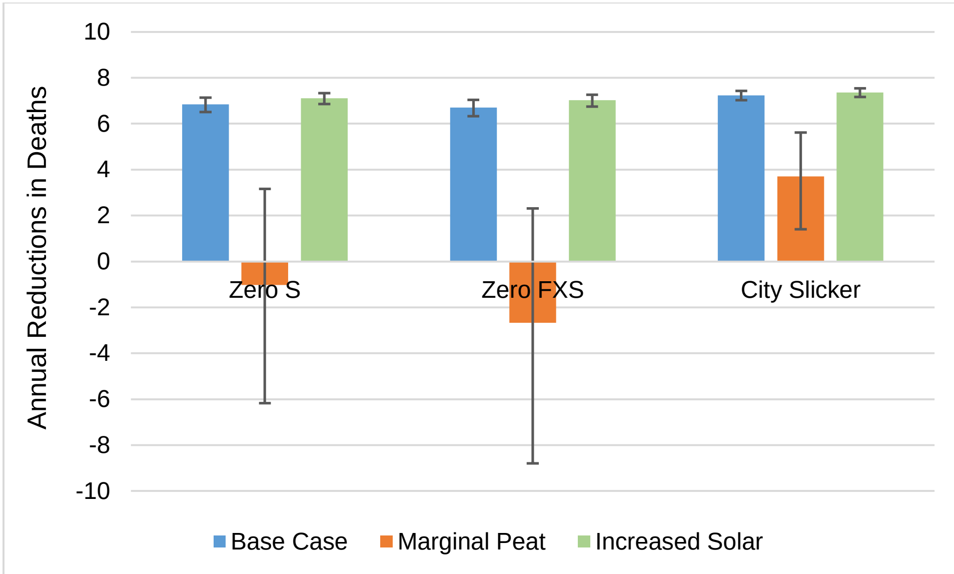


Figure 3.6: Reduction in death risk associated with motorcycle electrification by scenario. These values represent the annual reduction in deaths attributable to 30,000 electric motorcycles of each type replacing 30,000 conventional motorcycles driving an average of 25,000 km/yr. values below zero imply an increase in lives lost as a result of Primary and Secondary $PM_{2.5}$ emissions. Error bars represent the 90% confidence intervals for each motorcycle.

Figure 3.7 shows that among pollutants that see reductions when conventional motorcycles are electrified (CO_2, $PM_{2.5}$, NOx, CO, HC), the high mileage scenario maintains the ratio of reductions (e.g. a Zero S motorcycle produces a 43% reduction of CO_2 compared to the TVS motorcycle in the base case and in the high mileage case) with the absolute value of these emissions reductions increasing with the distance traveled. Similarly, SO_2 emissions in the high mileage case show increases that maintain the ratios observed in the base case electric to conventional increases but see increased absolute emissions. In the high mileage case, the distance traveled is roughly double that of the base case and thus emissions generated in all cases are roughly double the base case. This implies that electrifying the motorcycles of drivers at the upper end of the distribution produces the same relative reduction as the entire fleet. When considering total emission avoided, electrifying the high mileage drivers offers about twice the amount of reductions found when electrifying all drivers. On the other hand, electrifying high mileage drivers doubles the amount of SO_2 produced. This analysis highlights the potential to reduce greater absolute levels of emissions by focusing high mileage drivers, however, a tradeoff is created in doubling the amount of SO_2 emissions.

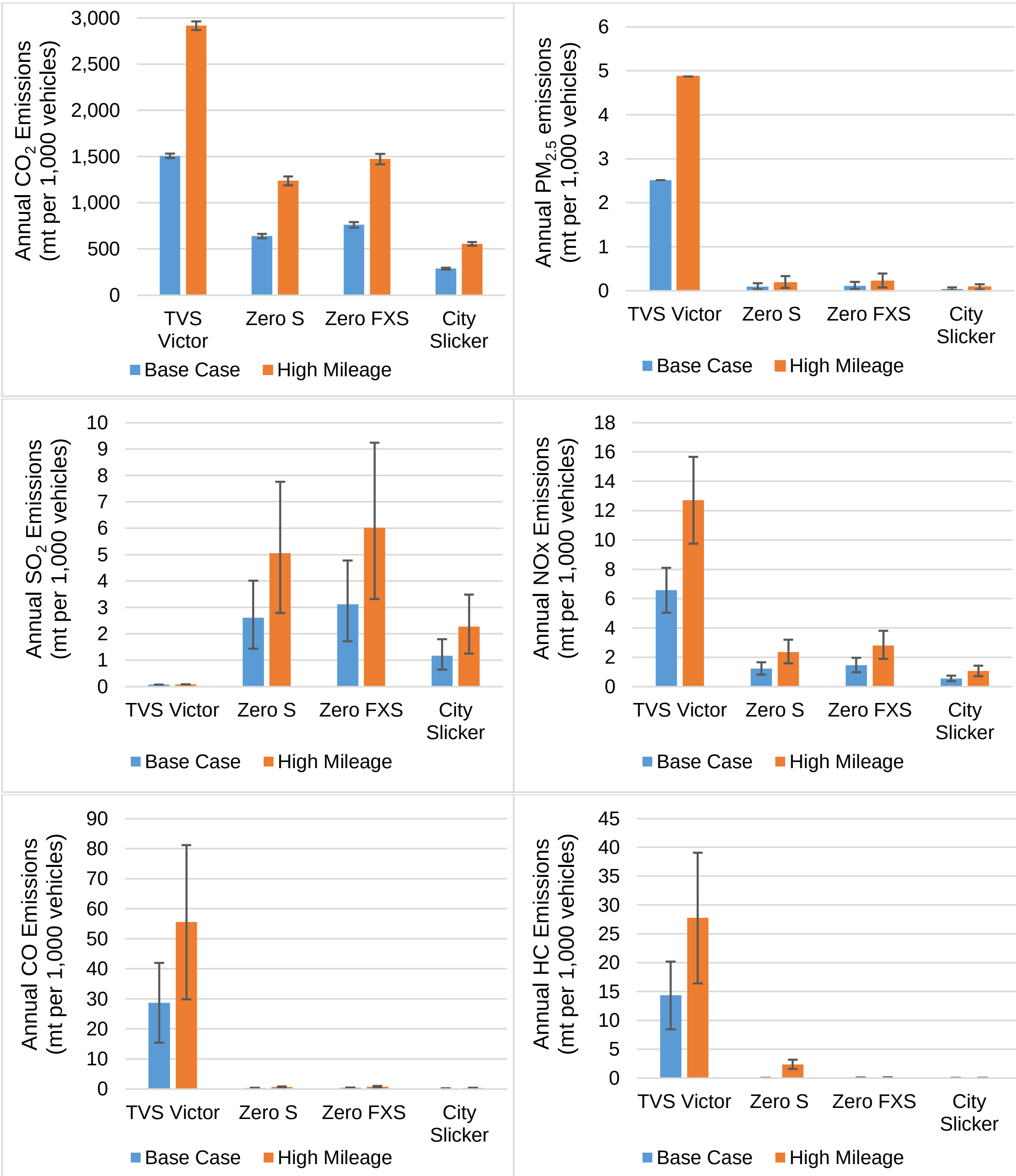


Figure 3.7: Estimates of mean emissions associated with conventional gasoline motorcycles and electric motorcycles by scenario. Base Case refers to emissions

generated by 1,000 motorcycles driving an average of 25,000 km/yr while High Mileage refers to emissions generated by 1,000 motorcycles driving an average of 49,000 km/yr. Error bars represent the 90% confidence intervals for each motorcycle and pollutant

The health impact analysis shown in Figure 3.8 reveals a relatively straight forward correlation of death reductions to mileage. Electrifying motorcycle drivers in the upper quartile of distance traveled results in an annual death reduction that is roughly twice the amount seen when electrifying the entire driver pool (Base Case). Naturally, because the base case includes these high mileage drivers, this analysis reveals that the upper quartile of drivers currently driving conventional motorcycles are linked with more deaths due to the additional pollution they generate. Targeting these drivers first in an electrification effort would help in realizing the greatest reduction in deaths immediately.

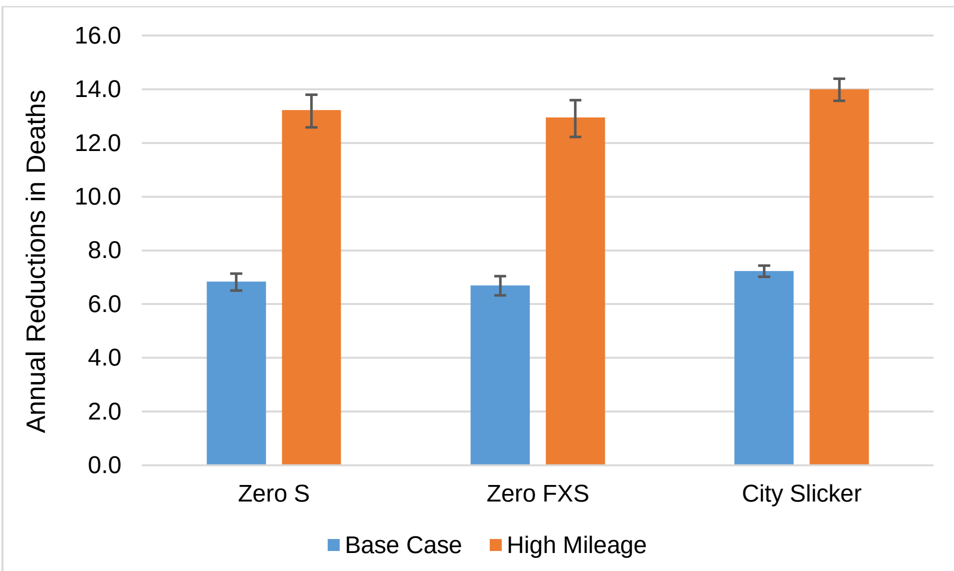


Figure 3.8: Reduction in death risk associated with motorcycle electrification by scenario. These values represent the annual reduction in deaths attributable to 30,000 electric motorcycles of each type replacing 30,000 conventional motorcycles driving an average of 25,000 km/yr in the base case and an average of 49,000 km/yr in the high mileage scenario. Error bars represent the 90% confidence intervals for each motorcycle.

3.4 – Discussion

In this paper we assess the emissions, health, and economic outcomes of electrifying motorcycle taxis in Kigali, Rwanda. By modeling fleet demand using observed driving distributions, we are able to estimate travel of this unique subset of all motorcycles which form the basis for all estimates. Our analysis reveals that emissions of key pollutants already identified by government officials (NOx, CO, HCs) as well as the greenhouse gas CO_2 and health risk $PM_{2.5}$ can be reduced via motorcycle fleet electrification, however, this is dependent on the marginal emissions and electricity draw. The sensitivity analysis reveals the importance that the composition of electric grid has in the potential reductions of emissions and annual deaths. If marginal emissions are closer to those of a high emission fuel such as peat, emissions of CO_2 and NOx may increase when motorcycles are electrified. Emissions of $PM_{2.5}$, CO, and HC show consistent reductions associated with electrification across all scenarios. Our analysis shows that the emissions of SO_2 associated with electrification are always greater than those of gasoline motorcycles. In regards to prioritization of motorcycles to be electrified, our analysis reveals that targeting high mileage drivers maintains the same directionality of emissions changes but amplifies the magnitude of emissions increases or decreases.

When considering health impacts, marginal emissions and the electricity draw alters the potential benefit found with electrification. Although the results using average emission factors reveal lower annual exposure and thus reductions in associated deaths, emission factors closer to those of peat-based generation can lead to increased deaths. The CSC City Slicker stands out among the electric motorcycles in that even when worst case emission factors are used, switching to this electric model results in a decrease of deaths annually. Under the high mileage scenario, electrifying the most demanding motorcycles amplifies the magnitude for health impacts while maintaining the directionality. However, we do not look into any other potential health impacts such as disease or infections that could be altered as a result of electrification. The electricity demand for every 1,000 motorcycles requires an estimated 0.2%-0.3% in additional electricity generation over the levels the grid currently produces. At the most ambitious target of complete electrification (within Kigali) of about 30,000 vehicles, this would add a maximum of about 10% to the electricity demand. It is important to note, however, that this may not require additional generation capacity if batteries could be charged during off-peak hours. These results highlight the importance of low emission electricity sources in combination with electrification. At a minimum, if electrification is pursued in Rwanda, fossil fuels such as peat should be avoided as the primary source of charging in order to maximize the benefits of electrification

Finally, the Levelized Costs of Driving analysis reveals that at least one of the electric motorcycle alternatives presented in this work is cost competitive over a five-year period, and cost competitiveness improves as vehicle life is extended. This comes with an important caveat however, as the some of the reason the City Slicker is cost competitive comes from its fuel efficiency, which is tied to its lower performance capabilities. The TVS Victor offers a maximum speed of 90 km/h whereas the City Slicker only offers 68 km/h. In Kigali, this may not be an issue as legal speed limits range from 40-60 km/h but outside the city, speed limits can increase up to about 80 km/h. Conversely, while the Zero brand motorcycles offer increased speed while maintaining emissions savings, the affordability of the models may prohibit adoption unless costs fall or subsidies are introduced.

This analysis provides a basis for policy makers to apply benefit-cost analysis principles to the transportation sector in developing countries. Note that as this analysis is from the perspective of the motorcycle driver, we do not include considerations of charging stations necessary for facilitating fast swapping. These stations would likely require private or government investments but are vital to potential motorcycle electrification. While not considered in this work, decision makers must also balance other priorities such as safety, stressors on transportation infrastructure, and public support of new transportation modes with costs, emissions, and health effects.

This research offers an important exploratory analysis into the electrification prospects of vehicles in sub-Saharan Africa. Our analysis indicates that electrification does not only offer emissions and health benefits, it may currently be economically feasible given certain conditions for expansion. Importantly, this work does not address other potential areas of concerns such as the social or cultural barriers of adoption that would require education and local and governmental agreement. This work is also applicable to other nations in sub-Saharan Africa which share high portions of motorcycle VMT and motorcycle-taxi commerce such as Nigeria, Ghana, Kenya, etc. As outlined, the incremental inclusion of electrification also allows gradual electrification and/or trials of electrified motorcycles that do not require the immense investments of other transportation projects.

Chapter 4: Electrification of multi-passenger transportation vehicles in Rwanda

As was established in Chapter 3, the transportation sector in Rwanda may serve as a key area to enable a sustainable, low-carbon energy transition. While the previous chapter focused on motorcycle electrification due to their high ownership in the country and city of Kigali, here I extend the study of vehicle electrification to higher capacity passenger vehicles: buses. This work builds upon the work done in chapter 3 and extends the analysis by examining the impacts on emissions, health, and economics of passenger bus electrification with a comparative analysis to the motorcycle electrification results. In this chapter we answer:

- How do tailpipe emissions from conventional diesel buses compare with well-to-wheel emissions from electric buses in Kigali, Rwanda?
- What are the health impacts associated with emissions from conventional buses compared to those of electric buses?
- What are the non-infrastructure costs associated with transit system electrification?
- How do the emissions and costs from multi-passenger transportation vehicles electrification compare to that of motorcycle electrification?

4.1 – Introduction

With transportation demand on the rise throughout the developing world, emissions associated with transportation are also likely to rise[11]. In Rwanda, current private vehicle ownership accounts for 21% of all trips taken[13] and projected demand is expected to result in an increase of private vehicle ownership of about 20% by 2030[61]. Despite private ownership increasing, in many developing countries private vehicle ownership rates will still be far below those of developed countries[11]. This shortfall in transportation demand versus ownership means many citizens will depend on public transportation and other means to travel. In Kigali, the capital city of Rwanda, 2014 public transportation (buses, mini-buses, and motorcycle taxis) use was approximately 73% of all motorized transport[13]. This high rate of public transportation use may provide opportunities to pursue adoption of more sustainable transportation technologies than the existing diesel-powered bus fleet, which would limit growth in associated vehicle emissions. The range of major transportation modes in Kigali include minibuses (25% of annual trips), which constitute the greatest portion of all-purpose daily trips, private transport (23%), Motorcycle taxis (21%), buses (18%) and walking (11%). While buses constitute the lowest share of motorized transportation within Kigali, the use of alternatively-fuel buses for public transportation has had considerable research and application undertaken in the developed and developing world[106–109].

The electrification of buses in particular offers the ability for developing countries to address two distinct issues of sustainable development, reducing harmful air quality pollutants (Sustainable Development Goal 3) and access to modern and sustainable energy (Sustainable Development Goal 7)[6]. In Rwanda, the primary concern for air quality is particulate matter where estimates and measurements have shown levels greatly exceeding the World Health Organizations (WHO) suggested limits[57]. Additionally, the composition of Rwanda’s electricity generation capacity is approximately 46% renewable (hydropower and solar photovoltaic) and 54% fossil fuels (in 2016), while diesel fuel used to power conventional buses. Through electrification, emissions that result from the combustion of diesel fuel – such as the greenhouse gas (GHG) carbon dioxide (CO_2) and fine particulate matter ($PM_{2.5}$) – may be replaced with a mix of generation less reliant on fossil fuel combustion. $PM_{2.5}$ is a well known carcinogen while also linked to cardiovascular and respiratory diseases[94,110]. In line with the aims of SDG 7, the switch in fuels also enables potential future benefits inherent with any future decarbonization efforts.

In conjunction with the Paris Agreement, Rwanda has submitted its National Determination of Commitment which, although sparse in specificity, does indicate planned infrastructure improvements for Bus Rapid Transit (BRT) systems[55]. Such systems combine infrastructure improvement and “smart” transportation systems with the goal of more reliable and efficient bus travel[111]. In the context of SSA and specifically East Africa, Raje et al. (2018) identify BRT implementation as a viable solution (in conjunction with other efforts, both technological and political) to aid the reduction of traffic pollution in Nairobi, Kenya[112]. However, this work is not intended to compare benefits of BRT vs electrification. In fact, electrification in conjunction with BRT systems may yield additional emissions reductions. Alam et al. (2014) examined the efficacy of BRT systems versus that of natural gas-fueled buses and found that in high-congestion scenarios, BRT systems are equivalent or better than CNG buses at reducing GHGs but combining both offers even deeper GHG reductions[113]. Analysis of real world emissions comparisons in China found that hybrid buses offered CO_2 reductions of 18%-29% and average NOx reductions of about 60% compared to the Euro V standard diesel buses[114,115]. If we consider life cycle emissions, Tong et al. (2015) examines multiple heavy duty vehicle alternatives and report electric buses (powered by natural gas electricity generation) were the only technology that resulted in emissions reductions (31% reduction of carbon dioxide equivalent compared to diesel buses)[116]. Note that the reliance on natural gas generation would represent a very conservative estimate in Rwanda given its relatively low-carbon generation mix (roughly 320 g/kWh based on our calculations). The literature presented indicates that bus electrification could help emission reductions targeted by Rwanda as a standalone effort or help amplify emission reductions if partnered with a BRT system in the future.

In this paper, we examine the emissions reduction potential of bus fleet electrification in Rwanda, we estimate the health risks associated with diesel bus emissions compared to those of an electric bus, and finally conduct a first order levelized cost of driving analysis. We model diesel bus emissions based on reported intercity bus demand then estimate the electricity consumption necessary to power an electric bus model of equivalent seating capacity. Emissions from both fuel sources are estimated to understand the pollution benefits and costs associated with fuel switching while estimates of $PM_{2.5}$ also contribute to health risk analysis. Finally, we conduct a comparison of the economic impacts of adopting a fleet of new diesel buses versus an electric bus fleet.

4.2 – Methods

4.2.1 – Bus demand data and modeling characteristics

A limited dataset provided by the Rwanda Utilities Regulatory Authority contains 10 days of a bus company's intercity trips with Kigali as the primary transport hub. The data include 44 buses, traveling between nine cities with a concertation southwest of Kigali. Additionally, the dataset contains the license plate numbers of each of the company's buses operating over the 10-day period and the number of ticketed passengers at select stops. While the data do not provide tracking of mileage driven, personal communication with RURA officials revealed average annual travel of 200,000 km per bus[117]. As the demand is reported as a point estimate, we apply a triangular distribution with minimum and maximum values at +/- 50% of the 200,000 km estimate to account for uncertainty and differentiation in bus routes. License plate numbers from the dataset were matched against registration data provided by the Rwanda Revenue Authority (RRA) to determine the make, model, and year of buses in service. As the registration data only comprises a portion of the vehicles registered from 2014-2017, only 18 of the 44 bus license plates were matched to corresponding registration record. All the matches were identified as Toyota Coasters with the majority (11) being recent model years 2013-2015, however, there were two 1996 model year vehicles with the remaining five failing between 1996 and 2013. Furthermore, the Coaster is the most represented bus in the registration database, accounting for over half of the buses and minibuses in the dataset (about 740 of 1400 buses and minibuses). Hence, we use the Coaster as the diesel bus in this analysis; adopting the manufactured reported fuel consumption of 6 kilometers per liter (kpl) or 16.67 l/100 km[118]. The capital cost for the diesel bus are taken from Lajunen and Lipman (2016)[109]. All costs updated and presented in 2018 dollars.

In order to conduct the comparative analysis, electric alternatives to the diesel buses are selected based on their seating capacity and the availability detailed operating characteristics. Table 4.1 contains the selected models of Proterra Catalyst brand buses which cover a span of operating ranges[119]. Note that the aim of this analysis is to provide a first-order estimate of the benefits and costs related to electrifying the fleet of intercity buses; we do not aim to provide a comprehensive analysis of all alternatives or optimization of the most viable electric bus alternatives. The operational efficiencies and ranges are as provided by the manufacturer and represent the base drivetrain option[119]. The low and high point represent the bounds as provided in the performance specifications and are treated as the low and high point for a triangular distribution, with the arithmetic mean serving as the “most likely” value in the distribution. Cost data is taken from the Proterra website for the base model (FC) and we assume conservative incremental increases of $25,000 for each higher range model.

Table 4.1: Characteristics of selected electric bus alternatives. The low and high values reported represent the limitations on battery capacity, driver behavior, and driving conditions as reported by the manufacturer.

Make	Model	Passenger Capacity	Fuel consumption (kpl)		Fuel Tank Capacity (L)		Purchase cost[109] (Thousand USD)
Toyota	Coaster	30	6		95		300
			Operational Efficiency (kWh/km)		Operating range (km)		Purchase cost[120] (Thousand USD)
Make	**Model**	**Passenger Capacity**	**Low**	**High**	**Low**	**High**	
Proterra Catalyst	FC	28	0.90	1.40	53	84	750
	XR	28	0.86	1.36	130	204	775
	E2	28	0.95	1.45	243	372	800

4.2.2 – Electricity generation and emissions factors

Electricity generation data from the Rwandan Utilities Regulatory Authority (RURA) details the monthly electricity generation from each power plant and fuel type in Rwanda throughout 2016[81]. The breakdown of generation by source is as follows: 43.3% hydropower, 32.3% natural gas, 11.6% diesel fuel, 9.8% heavy fuel oil, 2.3% solar, and 0.9% peat. The amount of electricity needed to power an electric bus in order to provide commensurate driving capabilities is calculated using the operational efficiency (kWh/km) presented in Table 4.1 multiplied by the demand estimates of the diesel bus (in kilometers) divided by a penalty which accounts for charging losses (assumed to be 9%) and transmission and distribution losses (triangular distribution with bounds of 15% and 23% and most likely value at 20%). Total fossil energy consumption is calculated using the estimated diesel consumption of the Coaster with diesel energy content of 38.7 MJ/L[50]. For the electric alternatives, total fossil energy consumption is a function of the fossil-based electricity generation, the respective energy content of each generating fuel, and the total electricity produced (including electricity generated and loss via charging, transmission, and distribution).

Estimates of emissions from electricity generation and diesel combustion in buses are determined using distributions of emission factors for power plants and prior research on diesel emissions (See *Table 4.2*). All distributions are input into a Monte Carlo Analysis (MCA) which allows us to account for uncertainty in emission factors associated with power plant emission abatement technologies, uncertainty in heating content of fuel, and uncertainty in bus tailpipe emissions. The MCA can represent the range of potential outcomes across air pollution emissions. Diesel bus emissions factors for $PM_{2.5}$ are adapted from Jamriska[121] et al. (2004) while CO_2, CO, NOx, and HCs are adapted from Cooper[122] et al. (2018). SO_2 emissions are derived through stoichiometric conversion using the sulfur content present in Rwandan diesel fuel (50 ppm)[84]. The electricity demand is multiplied by power plant emission factors for $PM_{2.5}$, CO, hydrocarbons (HC), and NO_x adapted from distributions in the European Monitoring & Emission Program and the European Environment Agency (EMEP/EEA) Emissions Inventory Guidebook[45]. Power plant CO_2 emissions for each fuel and plant type are adapted from the U.S. Environmental Protection Agency's GHG inventory[123]. The distribution of heat content values necessary to energy conversions are provided by the Energy Information Administration's Power Plant Operation Report[124]. The calculation for electric bus emissions is provided in Equation 4.1. Table 4.2 lists the mean, low, and high values of the emission factors used to calculate emissions from the grid (modeled as a triangular distribution). As in Chapter 3, this analysis uses average emissions factors as well as marginal emission factors using peat-based generation and an increased penetration of solar-based generation. In taking this approach, we do not include considerations for timing of battery charging which could affect emissions profiles at a given time period. Section 4.2.5 details our sensitivity analysis which assess the impact of an alternative grid composition and the potential impact of marginal emissions. Furthermore, with data limitations on bus routes and driving characteristics the diesel buses, we do not attempt to account for charging schedules or route optimization. The ranges provided for the electric buses are limiting factors that would be considered by purchasing companies based on their knowledge of demand and route length. As such, we make no assumptions about the optimal composition of an electric fleet in Rwanda, opting instead to provide the generation and emissions associated only with the distance driven.

$$Emissions_i = \sum_j \left(w_j \times \eta_j \times EF_j\right) \times OperEff_i \times Distance_i \qquad (4.1)$$

Where *i* denotes the electric bus models, OperEff is the reported operational efficiency, distance represent the extrapolated annual fleet distance, w represents the weight (percentage) of each generation type "j" used in the grid, *η* represents the heat rate of each plant type "j" in the grid (in GJ/kWh), and EF represents the emission factors for each plant type (in g/GJ of fuel input). Note that upstream emissions associated with fuel extraction, production, and transportation for electricity and transportation fuels, as well as vehicle and battery manufacturing, are outside the boundary of this analysis.

Table 4.2: Mean emissions factors for diesel combustion in buses [g/km] and electricity generation by source [g/kWh] Values in parenthesis indicate the lower and upper values of the triangular distribution.

Pollutant	**Diesel Bus**[121,122] **(g/km)**	**Thermal Diesel**[45,123,124] **(g/kWh)**	**Heavy Fuel Oil**[45,123,124] **(g/kWh)**	**Natural Gas**[45,123,124] **(g/kWh)**	**Peat**[45,123,124] **(g/kWh)**
$PM_{2.5}$	0.27 (0.13-0.41)	0.01 (0.00-0.03)	0.41 (0.01-1.00)	0.01 (0.00-0.01)	0.19 (0.08-0.30)
CO	260 (30–730)	0.31 (0.05–0.71)	0.17 (0.10–0.24)	0.34 (0.18–0.51)	0.28 (0.08–0.66)
HC	2.40	0.01	0.03	0.04	0.02

	(0.20–6.40)	(0.01–0.01)	(0.02–0.04)	(0.01–0.09)	(0.01–0.04)
NOx	52.5 (12.0–130)	1.04 (0.26–2.13)	1.90 (0.80–3.35)	0.83 (0.15–1.60)	3.52 (1.63–6.22)
CO_2	2,870 (560–7,860)	780	790	430	1,200
SO_2	0.013	1.9 (0.39–4.07)	8.65 (3.42–15.4)	0.002 (0.002–0.003)	25.6 (9.81–0.58)

4.2.3 – Health Impacts

As in Chapter 3, human health risks from air emissions are assessed using emission estimates from electricity production and diesel combustion from buses, intake fractions (iFs), and toxicity of $PM_{2.5}$ emissions from each vehicle and reported as additional mortalities based on average fleet travel. As discussed in Chapter 3, IFs estimate the portion of air pollutants a population is breathing in[71,85–87]. We use a one-compartment model to estimate the impacts of primary and secondary $PM_{2.5}$ emissions. Equation 4.2 provides the formula for one-compartment static iFs:

$$iF_{compartment} = \frac{BP}{uH\sqrt{A}} \tag{4.2}$$

Where B represents the average breathing rate of the population, P represents the population in a given area, u represents the wind speed, H represents the atmospheric mixing height, and A represents the land area. Wind speed and atmospheric mixing height are meteorological values provided by NASA's Global Modelling and Assimilation Office, as measured in Kigali in 2017. These values are provided in Chapter 3. Assumptions about the new electricity generation remain the same: we assume that the additional electricity generated for the electric buses is supplied with the country's generation mix and thus emissions factors are derived from the total generation mix, as opposed to any local generation mix across cities or regions, or from marginal generators or new added capacity. As health impacts for individual buses or even hundreds of buses are relatively small values, we calculate the number of attributable deaths using the entire recently registered fleet of approximately 1400 buses.

As with our approach in Chapter 3 of this work, we make the simplifying assumption that emissions from the electric grid occur in Kigali rather than at the location of the power plants across the country. In doing so, we hold the population, land area, and metrological values constant for emissions generated by conventional motorcycles and electric motorcycles. This assumption means that intake fractions will be the same for conventional and electric bus emissions causing the difference in emissions to drive the health impacts. In reality, emissions from each power plant would occur locally with a different population exposed to the emissions. We justify this assumption based on the population density of Kigali which is 3 to 5 times greater than that found in the rest of the country[93]. Given the density of Kigali, unless the dilution rate in other regions are 3 to 5 times greater than Kigali's, our intake fractions may represent the upper bound.

4.2.4 – Levelized Cost of Driving

As in the electric motorcycle analysis conducted in Chapter 3, we compare costs across the various bus models by normalizing the levelized cost of driving (LCD) adapted from Elgowainy et al. (2018) in the base case. We calculate cost per vehicle-kilometer traveled (VKT) as shown in Chapter 3 (Equation 4.3). Unlike Chapter 3, we do not include a premium for the electricity supplied to power the bus as these costs are not placed on the driver. Maintenance costs for diesel buses adapted from Lajunen and Lipman (2016) while they are halved for electric buses in accordance with Feng and Figliozzi (2013) to account for fewer moving parts[109,125]. A comparative cost analysis including the costs of motorcycles examined in Chapter 3 is included and accounts for passenger capacity to assess the changes in value based on bus size (See Section 4.2.6). All values used in this analysis are provided in Table 4.3 below.

$$LCD = \frac{\frac{i(1+i)^n}{(1+i)^n-1} \times CapCost + Maintanence}{VKT} + \frac{FuelPrice}{FuelEconomy} \tag{4.3}$$

Where *i* is the discount rate of the Rwanda Central Bank (8%) and n is the lifetime of the bus (here, taken as 12 years in the base case).

Table 4.3: Values used in the economic analysis. All costs presented are in 2018$.

	Base Case			Lower Capital Costs (electric only, Thousands)
	Price (2018 $, Thousands)	**Maintenance Costs**	**Fuel Costs**	
Toyota Coaster	$ 300	0.19 $/km	1.30 $/L (1.26 – 1.35)	$ 150
Proterra FC	$ 750	0.09 $/km	0.20 $/kWh (0.17 – 0.22)	$ 375
Proterra XR	$ 775	0.09 $/km	0.20 $/kWh (0.17 – 0.22)	$ 388
Proterra E2	$ 800	0.09 $/km	0.20 $/kWh (0.17 – 0.22)	$ 400

The analysis includes three additional scenarios:

1) Lower capital costs of the electric vehicles in consideration of future cost reductions. In this scenario, we assume costs of the FC is halved to $375,000 while the E2 is decreased to $500,000. We assume the XR is price is the mean of these two values, $437,500.
2) Increased lifetime of 20 years.
3) Both lower capital cost for the electric vehicles and increased lifetime considered.

4.2.5 – Sensitivity Analysis

As discussed in Chapter 3 of this document, the electricity grid in Rwanda is subject to change in the future and the resulting fuel mix would impact the results of this analysis. Additionally, marginal emission factors can play a significant role in the interpretation of final results. In order to account for the grid mix and marginal emissions, we examine two cases that assess alternative electricity mixes. First, we examine how marginal emissions and the introduction of more peat-based electricity generation would impact electrification efforts. Marginal emissions refer to the last electric plant used to generate electricity for to meet increased demand[82]. We do not have data on the marginal plant used to generate electricity demand created by electrification but this role is typically filled by dispatchable fossil fuel plants[82,97]. Depending on the marginal generator, marginal emission factors can be significantly different than average emissions factors which would lead to an underestimation of emissions[97–99]. Given the peat reserves in Rwanda (up to 155 million metric tons) and the peat power plant in construction (80MW), peat has the potential to significantly alter the generation mix[100–102]. As peat is one of the most polluting fossil fuels for power generation, we approximate the worst case impact of marginal emissions using all peat-based electricity[103]. We assess the new electricity generation from the 80MW plant over one year using a capacity factor of 0.53 as reported in Axelsson and Johnson (2017) with all other variables held constant[100]. We report the change in emissions observed for bus electrification under peat-based electricity generation as well as the change in health impacts.

The final case examines how an expansion of solar power into the grid mix instead of peat would affect the electrification results. In this scenario, we add 370 GWh of solar which equates to roughly 220 MW of solar installed using a capacity factor of about 0.19. This solar capacity factor is back calculated from the observed electricity production (~14MWh in 2016) and the installed capacity of the Giga Watt solar photovoltaic field (8.5 MW)[81,104]. While the 220 MW addition would roughly double the 2016 installed capacity, the added generation falls well short of potential annual solar generation in Rwanda which is estimated to be over 65 TWh[105]. Again, we report the change in emissions observed for bus electrification under solar-based electricity generation and the change in health impacts.

4.2.6 – Comparative assessment to motorcycle results

In order to offer a more comprehensive assessment of vehicle electrification in Rwanda, we compare the results of our motorcycle electrification results from Chapter 3 with those of the bus electrification presented here. The comparison looks at the benefits and costs of electrifying motorcycles versus those of electrifying buses. We compare the differences in emissions and cost of driving between vehicles per passenger-km traveled (PKT). Because these two modes of travel are inherently different (mass transit versus individual travel), these comparisons are only meant to add context to the discussion. Specifically, this comparison gives insight into some tradeoffs inherent in decarbonization efforts in the growing transportation sector of SSA. However, this analysis is limited to non-infrastructure costs which could make one technology more feasible than the other depending on conditions such as local policies and incentives, terrain, infrastructure layout, etc.[126–128].

In order to compare the emissions and cost of driving between motorcycle travel and bus travel, we normalize by PKT. We assume buses are running near capacity, modeling the average capacity as a triangular distribution with minimum, most likely, and maximum values set at 75%, 85%, and 100%, respectively. We assume fuel economy is not materially affected by number of passengers. We assume motorcycles only carry one passenger. Note that multi-passenger motorcycle rides are common in some SSA countries but are generally viewed as dangerous, prompting regulation to restrict the practice in some regions[129]. Emissions estimates are divided by the kilometers traveled multiplied by the average passenger load. As an example, the levelized cost analysis amends Equation 4.3 to include the average number of passengers transported by each mode. This new equation (4.4), provides us with the levelized cost of driving per passenger-km traveled (PKT).

$$LCD = \frac{\frac{i(1+i)^n}{(1+i)^n-1} \times CapCost + Maintanence}{VKT * AvgPassenger} + \frac{FuelPrice}{FuelEconomy * AvgPassenger} \tag{4.4}$$

4.3 – Results of Bus Analysis

4.3.1 – Emission estimates

Our emissions analysis indicates that electric buses offer considerable reductions of key pollutants, but not all pollutants are reduced due to electrification. Two pollutants of importance, CO_2 for its climate change implications and $PM_{2.5}$ for its health implications, show mean emissions levels that are respectively about 4.5 and 7 times less when diesel bus travel is replaced with electric bus travel. These new emission levels equate to total annual mean reductions of over 18,000 t of CO_2 and 4.5 t of $PM_{2.5}$ across all electric alternatives examined for the 1,400 buses in the fleet. Figure 4.1 highlights the results, with the bars representing the mean emission estimates and the error bars encompassing the 5th and 95th percentiles. Recall that these emission estimates are derived using average emission factors and the results for marginal emission factors are presented in Section 4.3.4. As shown, the diesel emissions exceed every electric alternative with slight observable differences across the three electric alternatives. These emissions are derived from a distribution of driving distance, the emission factors of diesel fuel, and the commensurate electricity needed to power the electric alternatives. While differences between the electric alternatives are relatively minimal when compared to the diesel bus, we do observe variance of about 400,000 kg of CO_2 and 60 kg of $PM_{2.5}$ between the XR and the E2 electric bus models. Of the three electric alternatives, the XR and the E2 are the most efficient (kWh consumed per km traveled) and the least efficient, respectively. In these emission estimates and those presented in Figure 4.2, the uncertainty of the diesel bus emissions is driven primarily by the diesel fuel emission factors presented in Table 4.2 while the electric alternatives have uncertainty driven by the emission factors and electricity loss. Uncertainty in CO_2 is driven primarily by the fuel efficiency of the vehicles while uncertainty in $PM_{2.5}$ is driven primarily by the emission rates of heavy fuel oil burned to produce about 10% of the country's electricity in 2016.

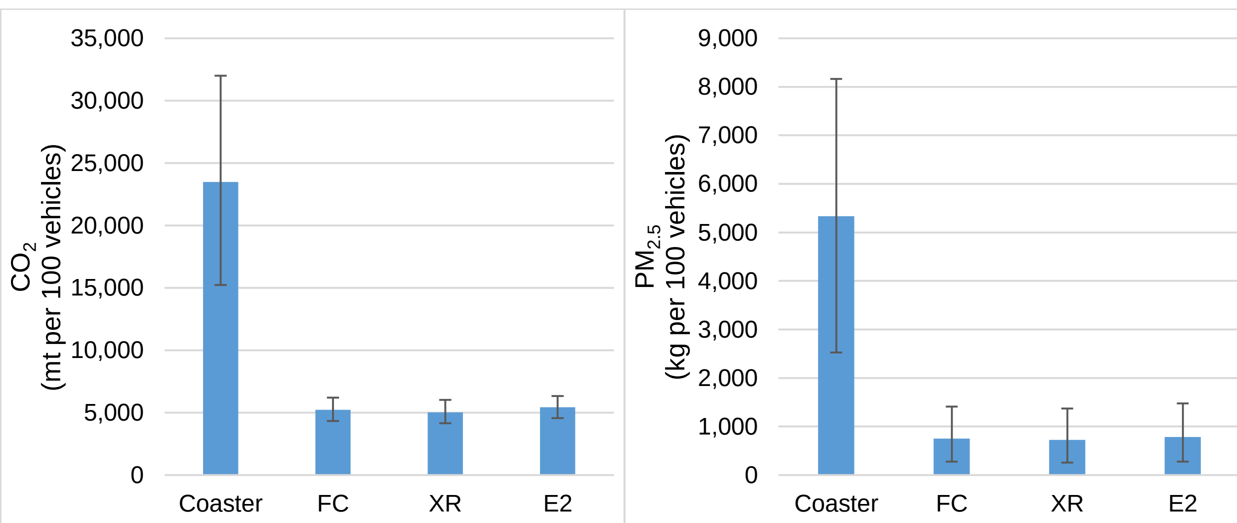


Figure 4.1: Estimates of carbon dioxide (CO_2) and fine particulate matter ($PM_{2.5}$) associated with conventional diesel combustion buses and electric buses driving an average of 200,000km per year. Mean emission results are presented with error bars representing the 90% confidence intervals for each pollutant. Note that CO_2 emissions are presented in metric tons (1,000 kg).

Figure 4.2 presents the results of our emission estimates for SO_2, NOx, CO, and HC. The results for SO_2 standout from those in Figure 4.1 and the rest of Figure 4.2 in that the diesel bus contributes to considerably less pollution than the electric alternatives. In fact, our estimates indicate that the electric alternatives contribute to emissions that are approximately 70 to 80 times greater than those from diesel buses. These results are driven primarily by the relatively low sulfur content of automotive diesel fuel in Rwanda (50 ppm) and the 10% electricity generation using heavy fuel oil which has a higher sulfur content. While the results for SO_2 standout, those of NOx, CO, and HC are qualitatively similar to CO_2 and $PM_{2.5}$. Mean diesel bus emissions of NOx, CO, and HC exceed those attributable to the electric alternatives by about 22, 20, and 5.5 times, respectively. These results along with those presented in Figure 4.1 highlight the emission benefits of electric buses with all pollutants except SO_2 decreasing many times the amount that diesel buses are producing. However, it is also important to consider how these emissions contribute to health impacts for the population.

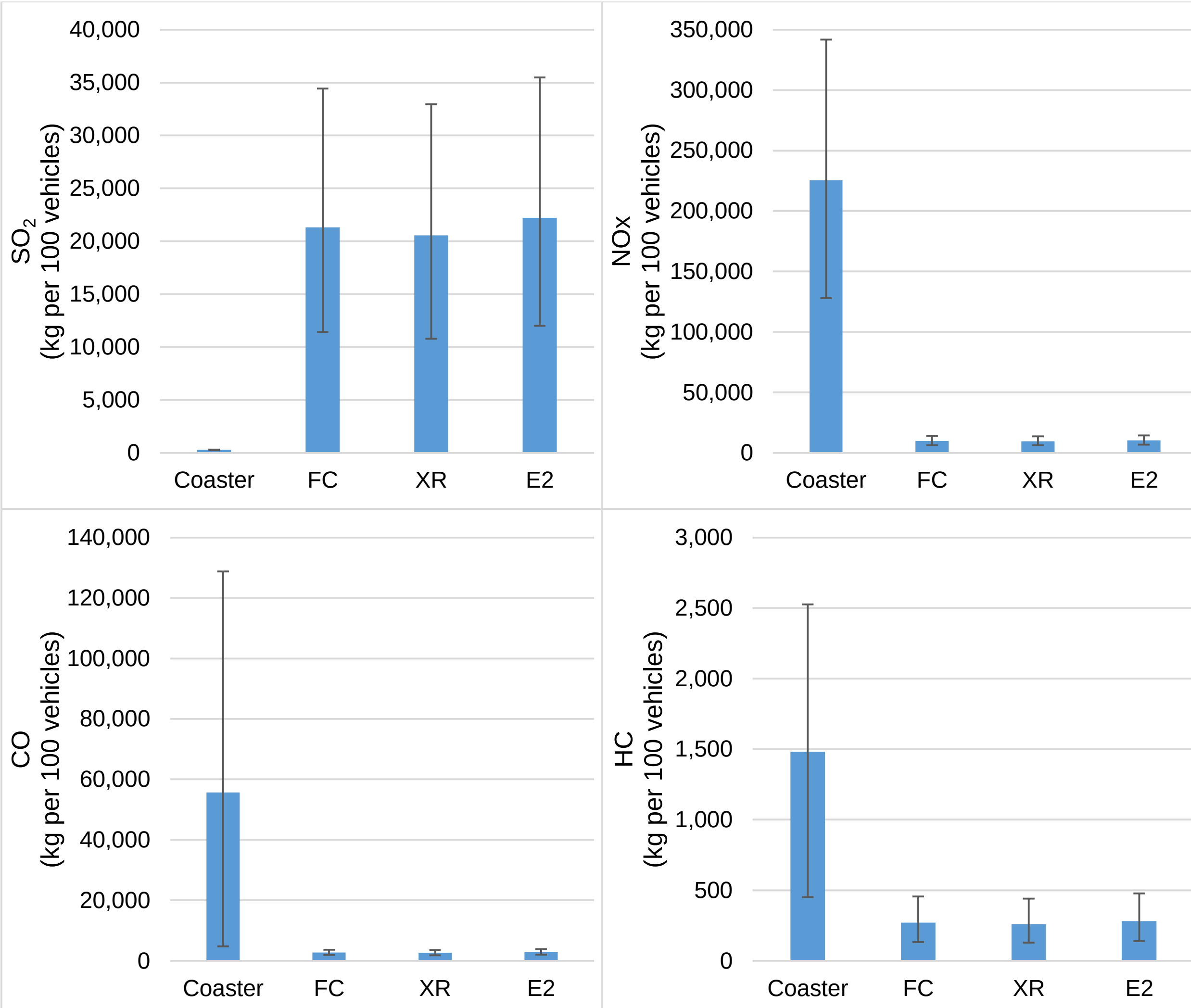


Figure 4.2: Annual estimates of emissions associated with conventional diesel combustion buses and electric buses driving an average of 200,000km. Mean emission results are presented with error bars representing the 90% confidence intervals for each pollutant.

4.3.2 – Health impacts of bus electrification

As stated in Chapter 3, our analysis indicates that for every additional kilogram of $PM_{2.5}$ inhaled annually, Kigali could see an increase of 5.06 deaths per year (refer to Equation 3.3 for calculation). This analysis considers the impacts across all recently registered buses (n = 1,400). Our analysis indicates that emissions from diesel buses contribute to roughly 19 deaths annually with 5th and 95th percentiles of 13 and 26, respectively. Conversely, all emissions generated to power the three electric bus alternatives contribute to roughly 2 to 4 deaths (90% confidence intervals). Figure 4.3 highlights the reduction in deaths from bus travel related pollution annually. Recall that this assumes the buses average 200,000 km of travel. Notice that despite the increase in SO_2 emissions associated with electrifying buses, the diesel buses emissions lead to roughly 7 times the attributable deaths. This is driven by three factors:

1. Over 1/3 of attributable deaths in all buses come from primary $PM_{2.5}$ and diesel buses emit 7 times more $PM_{2.5}$ than electric buses
2. As SO_2 emissions in diesel buses are relatively low, NOx emissions contribute to over 99% of secondary emissions intake with diesel bus NOx emissions over 20 times greater than those of electric buses
3. Despite the relatively high SO_2 emissions, NOx contributes to about 70% of secondary emissions intake from electric motorcycles, limiting the impact of the increased SO_2 emissions

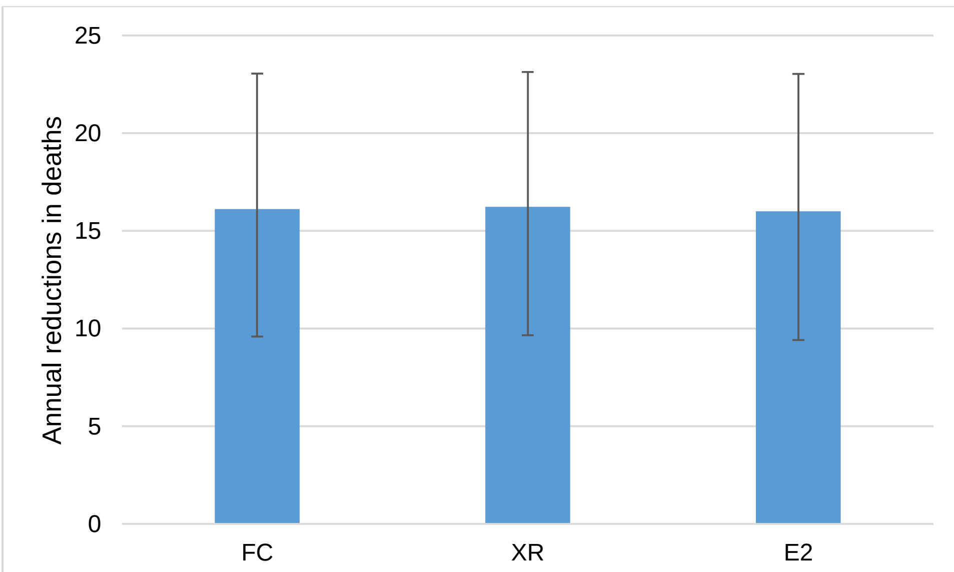


Figure 4.3: Reduction in annual mortality risk associated with bus electrification. These values represent the annual reduction in deaths attributable to emissions from 1,400 electric buses of each type replacing 1,400 conventional buses driving an average of 200,000 km/yr. Error bars represent the 90% confidence intervals for each bus's attributable deaths.

4.3.3 – Levelized cost analysis

The results of our levelized cost analysis is presented in Table 4.4 below. Across all scenarios examined, the diesel bus represents the cheapest option, but not under all scenarios. In the base case, the electric alternatives cost roughly 40% to 50% more per kilometer. Considering the 12-year lifetime of the base case, this equates to increased lifetime costs (present value) among the electric buses between $630,000 and $730,000 (2018 $). Under the low capital cost scenario, the electric buses become more cost competitive with the cheapest option, the FC, approximately $0.02/km more expensive. This equates to a present value lifetime difference in ownership of about $33,000. Extending the lifetime considered to 20 years results in decreased costs of ownership among all buses, with the largest reduction observed by the E2 model. However, under the increased lifetime scenario, the Coaster remains the dominant cost option. The final scenario examines both lower capital costs for the electric buses and a longer lifetime. In this scenario, all electric alternatives become more competitive with the Coaster with the FC dropping to cost parity. There is no timeframe where the E2, the electric alternative with the longest range, reaches cost parity with the Coaster.

Table 4.4: Mean levelized cost of driving across varying scenarios for all buses examined. All values are presented in 2018 dollars.

Vehicle	Base Case ($/km)	Low Capital Expenditures (Electric only) ($/km)	Longer Lifetime (n = 20) ($/km)	Low CapEx + Longer lifetime ($/km)
Toyota Coaster	0.60	n/a	0.56	0.56
Proterra FC	0.86	0.62	0.75	0.56
Proterra XR	0.87	0.65	0.75	0.58
Proterra E2	0.90	0.70	0.78	0.63

4.3.4 – Sensitivity Analysis Results

Our sensitivity analysis reveals that for most emissions, the grid mix and marginal emissions do not change the qualitative results found in the average emission case analysis. Despite the use of peat as the marginal electricity generating plant, the diesel bus emissions generate more CO_2, $PM_{2.5}$, NOx, CO, and HC. However, the use of peat does increase the emission of electric buses over those found in the base case using average emission factors. The largest increase is seen in SO_2 where peat generation increases the emissions of SO_2 by a factor of 8 across all electric buses. CO_2 and $PM_{2.5}$ emissions associated with electricity for electric buses from peat doubles over the base case. Across all electric buses, introducing solar electricity into the grid reduces emissions by about 60%.

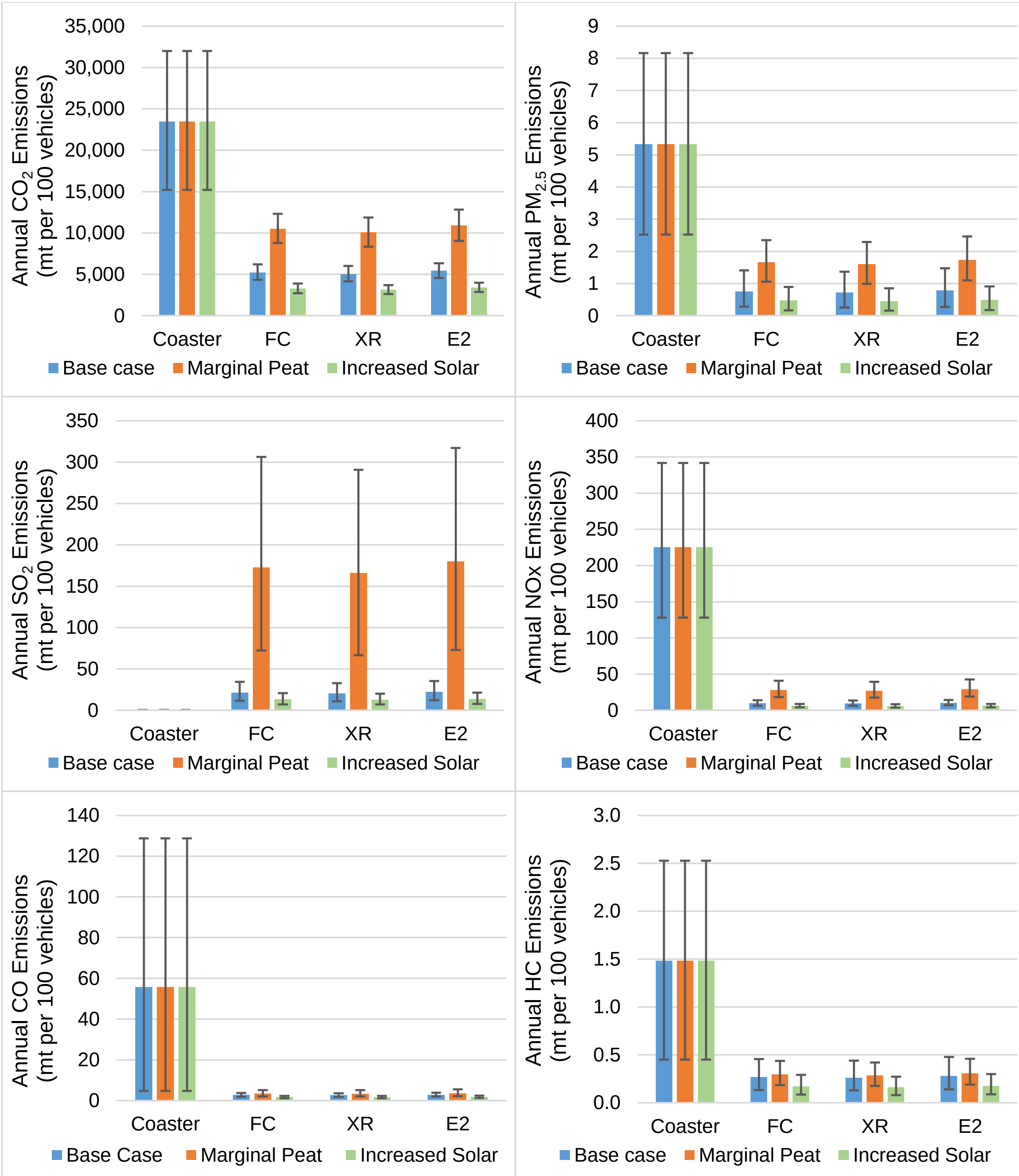


Figure 4.2: Estimates of mean emissions associated with conventional gasoline bus and electric bus by scenario. Error bars represent the 90% confidence intervals for each bus and pollutant.

While the emissions results were not significantly impacted by the marginal generation from peat, the health impacts associated with this scenario show significant decreases over the base case. In this case, the increase in SO_2 seen from peat based electricity results in a mean value of roughly 28 deaths (across all electric buses) which is greater than the total mean of deaths from both Primary and secondary $PM_{2.5}$ seen in conventional buses. Relying on peat causes an average increase in deaths from Emissions associated with peat electricity for the electric buses increases the average number of deaths by 12 to 15 people annually. Conversely, a grid mix incorporating more solar results in an additional life saved each year on average. These results highlight the importance of controlling SO_2 emissions as they are the sole pollutant associated with electric buses that exceed those of conventional buses and they drive the increase in lives lost.

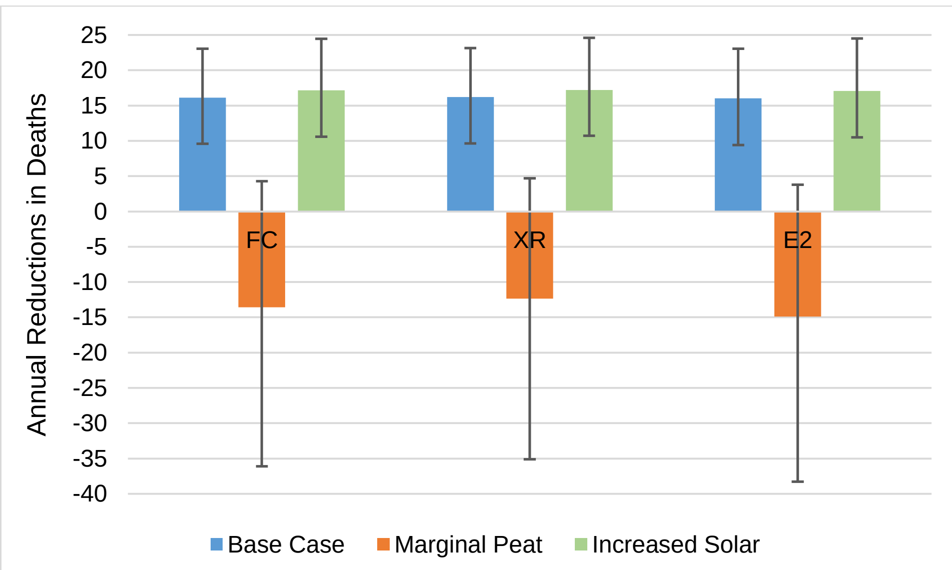


Figure 4.5: Reduction in death risk associated with bus electrification by scenario. These values represent the annual reduction in deaths attributable to 1,400 electric buses of each type replacing 1,400 conventional buses driving an average of 200,000 km/yr. Values below zero imply an increase in lives lost as a result of Primary and Secondary PM2.5 emissions. Error bars represent the 90% confidence intervals for each motorcycle.

4.3.5 – Comparative analysis

The emission comparison reveals that when normalized, pollutants from buses are lower than those from motorcycles in most cases. Compared to all motorcycles examined, the electric buses have as good or lower emission rates for all pollutants except SO_2. Table 4.5 highlights these normalized results providing the mean annual emission rates. While these results can be used to assess the effectiveness of pollution reduction among other things, it is important to recognize that motorcycles and buses are not perfect substitutes for one another. This analysis could be fitting for deciding which projects to attempt in pursuit of emissions reductions for the SDGs.

Table 4.5: Normalized comparison of emission rates by vehicle type. Values presented are the mean annual emissions per passenger-kilometer traveled. Values in bold represent the lowest emission rate in each mode of transportation. Shaded values represent the lowest emission rates across modes.

Vehicle	Passenger Capacity	Emissions (g/p-km)					
		CO_2	$PM_{2.5}$	SO_2	NOx	CO	HC
Motorcycles							
TVS Victor	1	59.9	0.1	0.003	0.261	1.14	0.57
Zero S	1	25.4	0.004	0.104	0.048	0.013	**0.001**
Zero FXS	1	30.3	0.004	0.124	0.058	0.016	0.002
CSC City Slicker	1	**11.4**	**0.002**	**0.047**	**0.022**	**0.006**	**0.001**
Buses							
Toyota Coaster	30	45.2	0.01	**0.001**	0.434	0.107	0.003
Proterra FC	28	10.7	0.002	0.044	**0.02**	0.006	**0.001**
Proterra XR	28	**10.3**	**0.001**	0.042	**0.02**	**0.005**	**0.001**
Proterra E2	28	11.1	0.002	0.045	0.021	0.006	**0.001**

The results of our comparative cost analysis are presented in Table 4.6. Unsurprisingly, the diesel bus has the lowest cost of driving due to its high passenger capacity and relatively low capital costs. Similarly, all buses, given their greater lifetime and greater travel, have lower normalized costs than the motorcycles with the closest differential (between the City Slicker and the FC) for motorcycle costs being 25% greater than the bus. Again, these values only capture the capital and use phase expenses, omitting any infrastructure costs. An assessment of the infrastructure costs needed to support electric motorcycles and/or electric buses would provide a more complete picture. Nevertheless, these results coupled with the emissions results shed light on the economic and environmental tradeoffs decision makers face.

Table 4.6: Normalized, levelized cost comparison. Values presented are the mean costs per kilometer traveled. Values in bold represent the lowest emission rate in each mode of transportation. Shaded values represent the lowest emission rates across modes.

Vehicle	**Passenger Capacity**	**LCD ($ per p-km)**
Motorcycles		
TVS Victor	1	0.049
Zero FXS	1	0.139
Zero SR	1	0.119
CSC City Slicker	1	**0.045**
Buses		
Toyota Coaster	30	**0.023**
Proterra FC	28	0.036
Proterra XR	28	0.036
Proterra E2	28	0.037

4.4 – Discussion

This work extends previous analysis of vehicle electrification in various countries by providing estimates of emissions, costs, and health impacts in a key region for the future of transportation. We build upon our work on evaluating motorcycle electrification by modeling diesel and electric bus options in Kigali given the demand data available. We examine the emissions, accounting for the uncertainties surrounding both vehicle emissions and electricity generators in SSA. Our MCA incorporates distributions in emission factors, energy, and travel requirements in order to generate estimates of diesel bus emissions and their electric counterparts. Using average emission factors, we find that emissions of all pollutants examined except SO_2 have the potential to be reduced by a minimum of 450%. When considering worst-case emissions under marginal emission factors from peat-based electricity generation, these results hold although the minimum reduction of emissions is roughly 220%. These results indicate that regardless of the marginal power plant, electrifying buses leads to minimum CO_2 emissions reductions of 220% while $PM_{2.5}$ is reduced by over 300%. The most drastic reductions are found in CO, which sees minimal reductions of about 1,500% when conventional buses are replaced by electric buses. On the other hand, SO_2 emissions are likely to increase significantly – at least 7,000% to 8,000% over the diesel buses – if bus electrification is pursued and the electricity is drawn from the current grid in Rwanda. Of relevance however, is that these new emissions could occur mostly at power plants mostly outside of urban areas, which could limit the impact on the urban population. Furthermore, our health impact analysis reveals that despite the increase in SO_2, the deaths that can be attributed to pollution from a bus fleet would decrease from about 19 to 3, annually with electrification. However, when the marginal power plant is peat, our marginal emission analysis reveals deaths could increase by about 70%. Thus, the health impacts are not robust enough to indicate if electrification can reduce annual deaths attributable to bus related air pollution. Finally, we find that the levelized costs of electric buses currently exceed those of diesel buses by at least 33% and that while extending the lifetime of the buses decreases this difference, it does not erase the cost differential completely. However, as the capital costs of electric buses fall, we observe signs that longer lifetimes allow parity between electric and diesel buses. Additional benefits in the way of decreased fossil energy are also present whereas electrification could save a 1,400 bus fleet approximately 40 million liters of vehicle diesel fuel and avoid about 1,100 GJ of fossil fuel energy.

This research extends the analysis conducted in Chapter 3, offering additional insights into vehicle electrification in Rwanda, but also more generally in emerging economies throughout SSA. Despite projected vehicle ownership increasing in SSA, the majority of the population still requires public transportation for travel and as travel increases, electrification provides a crucial step to ensuring long-term sustainability. As the environmental benefits of electric buses have led to their deployment in developed and economically strong developing countries around the world, the cost of implementation remains a challenge for emerging economies. Yet, the prospect of future cost reductions makes large scale deployment in emerging economies more feasible although aid or incentives may still be required to develop the necessary supporting infrastructure. As discussed in Chapter 3, decision makers will have to consider other priorities such as safety, stressors on transportation infrastructure, and public support of new transportation modes before implementing vehicle electrification. Nevertheless, public transit electrification could play a crucial role in achieving the Sustainable Development Goals as countries commit to lower greenhouse gas and harmful air pollutant emissions.

Chapter 5: Conclusions and policy implications

If the world is to move towards sustainable growth and development, we must acknowledge the role that developing countries will play and support their efforts in pursuing sustainability. Nearly all of the projected population growth through 2050 will occur in developing countries. In fact, over half of the world's population growth through 2050 is expected to occur in Africa[3]. This increase in population will require more electricity and transportation services in a region where electricity access and transportation already occurs at rates much lower than developed countries[10,130]. Globally, the electricity sector and transportation sector currently contribute to nearly 40% of GHG emissions[131]. However, electricity access and increased access to transportation are paramount to achieving the UN's sustainable development goals. It is thus important to ensure that these increased needs are met with low-carbon energy.

Ensuring a stable electricity grid with little to no power outages ensures that grids reliant in fossil energy are limiting fossil energy consumption and those currently reliant on low-carbon energy mixes are not being supplemented by fossil fuels in the form of backup generators. Additionally, addressing the increased need of transportation and vehicle ownership through electrification offers multiple benefits in the form of stabilizing demand of electricity services, reducing fossil fuel reliance, and reducing air pollution. As an added benefit, air pollution associated with power outages and the transportation sector lead to harmful health impacts that could be mitigated with available techno-economic interventions.

While this work focuses on UN Sustainable Development Goal (SDG) 3 and SDG 7, it should be noted that many other sustainability goals are related to the outcomes of increased access to reliable electricity and decreased air pollution. Although the SDGs are legally non-binding, most of them have targeted achievement dates of 2030-- about a decade away. In order to achieve these, it's important that all countries involved find cross-cutting solutions that allow for efficient and sustainable resource allocation. SDG 1 calls for the eradication of poverty and while the relationship between electricity access and poverty has some uncertainty surrounding it, there is a base level of access correlated with reducing poverty[36,132–135]. Researchers have also argued that ending hunger (SDG 2) may relate to electricity access indirectly (e.g. lost economic production due to poor lighting leads to lower income which also ties into SDG 1 and SDG 8 (ensuring decent work and economic growth)[136]. SDG 4 (ensuring quality education) and SDG 5 (gender equality) are also directly and indirectly related to electricity access. Through electricity access, certain chore times are reduced allowing time for women and children to attend school while also providing lighting for studying at night followed by communication resources (television, radio, and internet access) derived from electricity[137–139]. SDG 9 (industry, innovation, and infrastructure), SDG 11 (sustainable cities and communities), and SDG 13 are all directly related to resiliency and reduction of power outages[140,141]. This exploration highlights the interdependence of sustainability and reliable electrification and energy services and emphasizes how important electricity is to a more equitable future in the developing world.

5.1 – Summary of Results and Policy Recommendations

This section summarizes the results and key takeaways from the analysis laid out in this body of work.

5.1.1 – Chapter 2: Sustainability implications of electricity outages in sub-Saharan Africa

- To what extent do power outages alter fossil fuel consumption for electricity generation throughout sub-Saharan Africa?

Power outages lead to increased fossil fuel energy consumption in every country analyzed. The increase is greatest in countries that have high proportions of low carbon electricity generation. We observe consumption of fossil energy (megajoules of fossil fuel) that are up to 1,000 times greater than the baseline consumption levels in countries that are most dependent on hydropower (e.g., DRC, Ethiopia). Furthermore, even countries that had a significant share of fossil fuel consumption (e.g., Niger, South Africa) in their grid still see an increased fossil energy consumption of 50%. This implies that even as low carbon generating technologies are deployed in SSA, if power outages remain a frequent occurrence, the use of diesel generators will negatively offset some of the low carbon benefits. As many SSA countries do not have native oil resources[142], we recommend governments in SSA that are concerned about energy independence explore reducing power outages as a means of reducing dependence on imported diesel fuel used in generators.

- How does this change in fossil fuel consumption affect air pollution emissions throughout the region?

Electricity provided by diesel generators during power outages result in increased $PM_{2.5}$, NOx, and CO (mean values) in all countries examined. This body of work has discussed the health impacts of primary $PM_{2.5}$ and secondary $PM_{2.5}$ and while this chapter does not explore health implications, $PM_{2.5}$ is an important pollutant to track and using diesel generators to provide electricity that would have otherwise been provided by the grid increases its emissions. Mean emissions of CO_2 increase in most countries, although countries with a high reliance on coal heavy electricity generation could see decreases in these emissions. The countries that see higher emissions of CO_2 when replacing grid electricity with backup generators are Niger (mean results show increased CO_2 during backup generation) and South Africa (results within the 90th percentile confidence interval show increased CO_2 during backup generation) which both rely on Coal heavily for electricity generation. Similarly, SOx emissions increases in countries most reliant on fuels with higher sulfur contents. If power outages are not addressed, as countries decrease the share of fossil fuel-based electricity generation, fuel switching triggered by backup generators replacing grid electricity will result in increased emissions across all pollutants. In countries where we do see increases of pollutants, emissions can increase up to 55 times those seen from grid-based electricity generation. We recommend investments in reliability of the existing grid (and ensuring reliability for new connections) should be part of the plans for achieving the Sustainable Development Goals in SSA countries. These investments may need to come from outside development and aid organizations but reductions in power outages ensure reduced emissions even as the grid is expanded to previously unelectrified populations.

- What are the costs associated with backup diesel generation and how do they compare with grid-based generation?

The cost of backup electricity exceeds the price consumers paid for electricity in every country analyzed. The smallest differential between diesel generator-based electricity and grid based electricity is observed in Angola (USD $0.13/kWh replaced). The largest differential is observed in Zambia (USD $0.53/kWh replaced). This correlates to a relative increase of 2.6 and 8.8 times that of the grid, respectively, with the lowest relative increase about 1.2 times that of the grid (Niger). This was an expected result as backup generation is typically more expensive than grid electricity but the magnitude of cost increase is nonetheless significant given the relative low economic development of many SSA countries. The expenses incurred by the population represent a burden caused by avoidable power outages. Additionally, households who cannot afford a generator or the increased cost of generation are left without power. Furthermore, the prices of electricity in many countries do not cover the cost of generation, transmission and maintenance, resulting in a pricing model that does not adequately recover the costs of providing power[17,33,143,144]. Conversely, given the fact that many SSA countries have utilities that do not charge the cost of generation and transmission, there may be an incentive for one time infrastructure improvements as a means of reducing future losses. While these initial investments may need to come in the form of aid, the case can be made that stabilizing the grid allows economies to reduce expenditures on backup power, directly benefitting the population of each country. Thus, grid stability arguably increases reliable energy for many SSA citizens while increases their spending power.

5.1.2 – Chapter 3: Motorcycle-taxi Fleet electrification in Kigali, Rwanda

- How do tailpipe emissions from conventional motorcycles compare with power plant combustion emissions associated with electric motorcycles in Kigali, Rwanda?

Our analysis indicates that three of the six pollutants ($PM_{2.5}$, CO, and HC) considered have significantly more emissions associated with conventional motorcycles than electric motorcycles while two additional pollutants (CO_2 and NOx) can see reductions but depend on marginal emissions factors and the differences in electricity draw associated with electric motorcycle efficiency. This is driven primarily by the proportion of electricity generation being low carbon with hydropower representing the largest source of generation (43%) and relatively low carbon with natural gas contributing to 32% of generation. However, SO_2 emissions associated with conventional motorcycles are estimated to be significantly less than those associated with electric motorcycles. In fact, electric motorcycles generate SO_2 at rates that are 16 to 340 times that of conventional motorcycles depending on marginal emission factors. This is driven primarily by the low sulfur content of Rwandan gasoline and the electricity mix which includes heavy fuel oil and peat which have significantly higher sulfur emission factors than other generation sources[145]. These results indicate that key emissions can be reduced by electrifying the fleet of conventional motorcycles although increases in SO_2 emissions presents a tradeoff. If more peat based generation is introduced into the mix such that it becomes the marginal generating unit, emissions of SO_2 increase even more while emissions of CO_2 and NOx potentially outpace those of conventional motorcycles. These tradeoff could be reduced significantly or eliminated altogether if low sulfur or non-fossil fuel based electricity generation is increased.

- What are the health impacts associated with emissions from conventional motorcycles compared to those of electric motorcycles?

Our analysis reveals that for every additional kilogram of $PM_{2.5}$ inhaled by the Kigali population, there are about five attributable deaths. This is distinct from each kilogram emitted, as not all emissions will ultimately be inhaled. We look at deaths attributable to primary and secondary $PM_{2.5}$ ($PM_{2.5}$ generated indirectly from SO_2 and NOx emitted into the atmosphere) produced as tail-pipe emissions from conventional motorcycles and emissions from power plants generating electricity to power electric motorcycles.
Any decrease in deaths attributable to motorcycle electrification are dependent on the marginal emission plant and the efficiency of the electric motorcycle. Across the city-wide fleet of 30,000 vehicles, we calculate about 7.6 deaths annually that are attributable to conventional motorcycles. This represents roughly 0.3% of all deaths due to ambient air pollution in Rwanda[60]. When marginal emission factors approach those of peat-based electricity generation, emissions associated with electric motorcycles could increase the number of annual deaths instead of reducing them. On the contrary, the results for emissions associated with electric motorcycles derived using average emission factors indicate attributable deaths are virtually zero with less than 0.5 deaths annually. The City Slicker electric motorcycle is an exception to this and due to its

higher efficiency it reveals annual deaths may be reduced even with peat as the marginal generating plant. However, the maximum health benefits are realized when peat is avoided and thus we recommended that peat-based electricity should not power vehicle electrification.

- What are the non-infrastructure costs associated with motorcycle fleet electrification?

We assess non-infrastructure costs as the levelized cost of driving for each motorcycle examined. These costs are assessed across a distribution of annualized driving distances and reported in $/km. In the base case, our analysis reveals that the cheapest normalized option is the electric City Slicker motorcycle despite its larger capital cost but the difference in the TVS Victor and the City Slicker is only three-tenths of one cent per kilometer. The remaining electric motorcycles, however, have mean LCODs that are 2.9 and 2.4 times that of the conventional motorcycle. We examine three alternative scenarios varying capital expenses, lifetime, and a combination of both factors. The first alternative scenario examines lower capital expenses for the electric motorcycles only and reveals that the Zero brand motorcycles maintain the highest LCOD (1.7 and 1.6 times that of the conventional option) while the City Slicker remains the cheapest option but gets about 30% cheaper than the base case. The second alternative scenario examined longer lifetimes which revealed no qualitative differences as the motorcycles maintain the same cost order while all getting cheaper. The final scenario combined the previous two alternative scenarios and decreases the gap in costs between the Zero brand motorcycles with the conventional motorcycle to about $ 0.02/km or about 1.5 times greater. In all scenarios, the speed limited City Slicker is the least costly option due to its relatively low capital cost and high efficiency (kWh/km). As the developed world looks to assist the developing world in emission reductions, we recommend vehicle electrification programs should be explored as a potentially cost effective means of reducing current emissions while ensuring future transportation growth is met sustainably.

5.1.3 – Chapter 4: Electrification of multi-passenger transportation vehicles in Rwanda

- How do tailpipe emissions from conventional diesel buses compare with well-to-wheel emissions from electric buses in Kigali, Rwanda?

Our analysis highlights the potential to reduce emissions when electrifying buses. Regardless of the use of marginal or average emission factors, we observe emissions reductions across several key pollutants but similar to the Chapter 3 analysis, SO_2 emissions show increases as opposed to reductions. Mean emissions of CO_2, $PM_{2.5}$, NOx, CO, and HC from diesel buses are about 4.5, 7.1, 23, 20, and 5.5 times greater than the electric alternatives, respectively. As with Chapter 3, the electric alternatives benefit from the grid mix which sources a major portion of generation from non-fossil fuel plants. On the contrary, SO_2 emissions see significant increases with electrification. The electric alternatives emit SO_2 at a rate that is 70 to 80 times greater than the conventional diesel bus. This result is driven by the low sulfur content of Rwandan automotive diesel fuel which is three times lower than that of automotive gasoline[145]. These results are in line with other literature examining diesel buses and alternative fuel buses in the developing world[114,115]. However, this analysis includes SO_2 estimates which show increases and requires decision makers in Rwanda and other SSA countries to weigh the costs and benefits of electrification given their current grid mix and future grid possibilities that could make electrification more or less attractive for emission reductions.

- What are the health impacts associated with emissions from conventional buses compared to those of electric buses?

Tail-pipe emissions from 1,400 diesel buses in Kigali contribute to roughly 19 deaths annually. If marginal emission factors are similar to those of a peat power plant, electrification will lead to an increase of 70% more deaths annually than diesel buses. Deaths. Using average emission factors, we see that electric buses contribute to roughly 3 deaths annually for an average reduction of 16 deaths. This analysis includes primary $PM_{2.5}$ and secondary $PM_{2.5}$ (from SO_2 and NOx) and show that the marginal emissions of SO_2 emissions determine if electrification of buses will lead to less deaths than diesel buses. In order to ensure a reduction in deaths, any vehicle electrification must avoid peat and high sulfur fuels as the marginal generating source. Maximum health benefits can be achieved by pursuing renewable energy sources such as solar power in conjunction with vehicle electrification.

- What are the non-infrastructure costs associated with transit system electrification?

In all scenarios examined, the levelized cost of driving diesel buses are either the cheapest option, or tied for the cheapest option. In the base case, the diesel bus is at least $0.20/km cheaper than the electric alternatives due to the high purchase costs of the electric alternatives. The cost difference across all electric models represents a 40% to 50% premium over the diesel bus. When considering the lower capital cost for the electric models, the price differentials drop significantly bringing the range of premiums for electric models down to just 2% to 17%. Under the extended lifetime scenario, the electric premium reduces across all models to a range between 34% and 41%. The final scenario examining lower capital expenses with extended lifetime, the Proterra FC model reaches parity with the Coaster while the more expensive XR and E2 models maintain a 5% and 13% premium, respectively. This analysis highlights the long-term benefits and potential for electric buses but does bring the economic viability of electric buses into question in emerging economies due to the higher cost premiums in the short term.

- How do the emissions and costs from multi-passenger transportation vehicles electrification compare to that of motorcycle electrification?

The final analysis of this chapter compares the normalized emissions and costs from the bus electrification analysis to those of the motorcycle electrification analysis in chapter 3. The results generally show that the electric multi-passenger buses have normalized emissions rates that are lower than or equal to all other vehicles in the analysis. Electric buses have the lowest emissions rates of CO_2, $PM_{2.5}$, NOx, CO, and HC, although, the electric motorcycles share the lowest emission rates of HC. SO_2 continues to stand as the sole outlier in the emissions as the diesel bus, which benefits from strict automotive diesel sulfur standards, demonstrates the lowest emissions rate. On the cost side, all motorcycles examined have higher costs per passenger kilometer with the diesel bus as the cheapest option. The cheapest motorcycle option (City Slicker) is almost twice as expensive as the cheapest bus (Coaster). When only considering the electric options, the City Slicker maintains a cost premium of about over the cheapest electric bus (FC). Excluding infrastructure costs, this analysis shows a cost advantage for buses as a whole and present electric buses as the best electrification option within the boundaries of this body of work.

Appendix for Chapter 2

This supplementary document includes input distributions, modeling characteristics, and additional results of our analysis.

Additional Figures

The mean weighted-average carbon monoxide emission factor for grid electricity in 2014 are provided in Figure A1. This figure reports the mean from the Monte Carlo simulations, which accounts for uncertainty in emissions factors for power plants with different efficiencies and pollution control technologies. Nigeria has the highest CO emissions of about 0.33 kg/MWh generated.

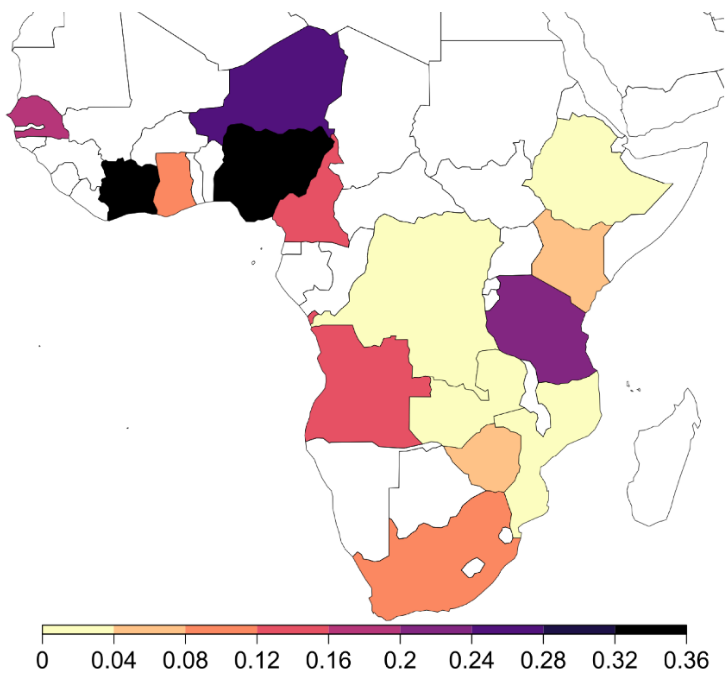


Figure A1: Mean Weighted-Average Carbon Monoxide Emissions Factors for Grid Electricity by Country in 2014. Countries shown in white were not included in the analysis.

Figure A2 shows the net changes in annual CO emissions that result from backup generators. As in Figure A2 in the main paper, the results in this figure are normalized by population that has access to electricity in each country in order to allow a comparison across countries of different population sizes. Figure A2 represents the range of results from our Monte Carlo simulations. Median values in Figure A2 are represented by an black line. Our analysis shows Nigeria produces the greatest median CO emissions at about 0.4 kg/person with electricity access.

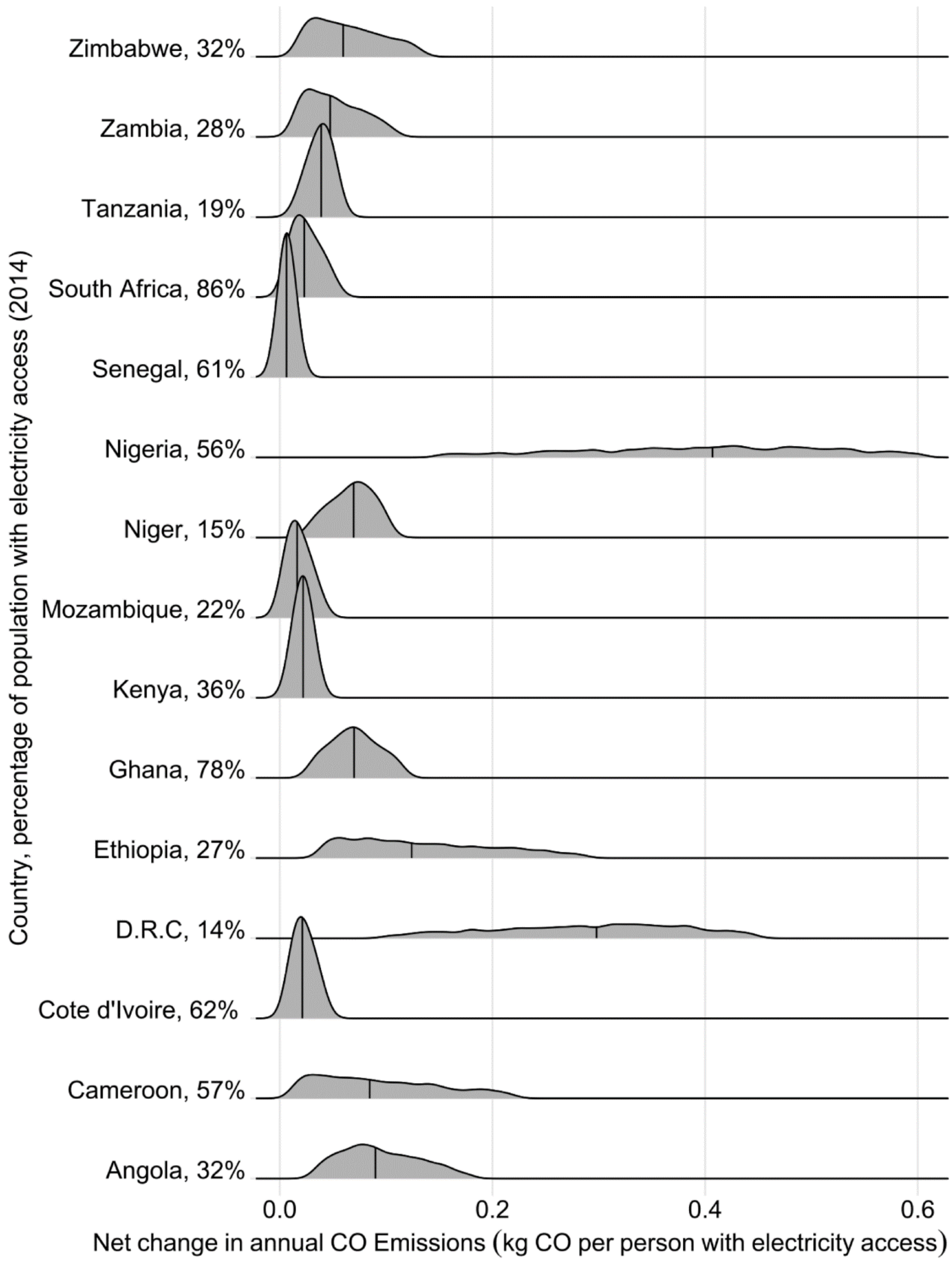


Figure A2: Ridgeline plots of normalized carbon monoxide emissions from backup diesel generators replacing grid-based electricity. The country labels include the percentage of each country's population that has access to electricity (2014 values). The distributions of each country reflect the 90th percentile confidence interval of outputs *observed from our Monte Carlo Analysis with the y-axis indicating frequency of observance. Median values in each country are represented by black lines.*

Additional Tables

Table A1 shows the weighted emissions factors for electricity from the grid for each pollutant for each country in our analysis. Values represent tons of each pollutant per MWh of electricity generated by the grid. The 90% confidence intervals appear in parentheses. Note that CO_2 emissions factors are not treated for uncertainty. Values less than 5x10^-4 are reported as negligible.

Table A1: Weighted emission factors by country. Mean values are provided with 90% confidence intervals provided in parenthesis.

Country	**kg of CO_2/MWh**	**kg of $PM_{2.5}$/MWh**	**kg of NOx/MWh**	**kg of CO/MWh**	**kg of SOx/MWh**
Angola	363	0.021 (0.007-0.038)	0.541 (0.209-0.948)	0.151 (0.038-0.298)	1.237 (.337-2.451)
Cameroon	173	0.022 (0.006-0.042)	0.406 (0.223-0.596)	0.121 (0.067-0.184)	0.751 (0.259-1.36)
Cote d'Ivoire	454	0.042 (0.011-0.082)	0.923 (0.362-1.528)	0.326 (0.189-0.467)	0.747 (0.196-1.445)
D.R.C	1	Negligible	0.001 (0.001-0.002)	0.001 (0-0.001)	0.001 (0-0.002)
Ethiopia	1	Negligible	0.001 (0-0.003)	Negligible	0.003 (0-0.006)
Ghana	247	0.044 (0.007-0.091)	0.366 (0.197-0.55)	0.089 (0.057-0.122)	0.88 (0.226-1.706)
Kenya	168	0.055 (0.007-0.115)	0.354 (0.204-0.525)	0.056 (0.026-0.092)	1.342 (0.454-2.439)
Mozambique	41	0.001 (0-0.001)	0.08 (0.020-0.143)	0.033 (0.018-0.047)	Negligible
Niger	1053	0.120 (0.05-0.189)	2.493 (1.343-3.95)	0.276 (0.114-0.479)	16.69 (4.274-31.67)
Nigeria	416	0.007 (0.004-0.011)	0.802 (0.201-1.436)	0.328 (0.184-0.474)	0.002 (0.002-0.003)
Senegal	616	0.294 (0.037-0.625)	1.517 (0.802-2.311)	0.183 (0.121-0.247)	6.444 (1.824-12.19)
South Africa	1002	0.276 (0.2-0.351)	4.553 (3.93-5.38)	0.096 (0.062-0.136)	7.726 (6.178-9.458)
Tanzania	389	0.064 (0.012-0.131)	0.798 (0.426-1.192)	0.232 (0.146-0.317)	1.405 (0.444-2.581)
Zambia	18	0.01 (0.001-0.021)	0.047 (0.024-0.075)	0.005 (0.003-0.006)	0.213 (0.058-0.408)
Zimbabwe	675	0.132 (0.096-0.168)	2.179 (1.88-2.573)	0.074 (0.048-0.104)	3.7 (2.966-4.525)

Table A2 shows the absolute change in net annual emissions that result from reliance on diesel backup generators during grid outages. The table includes the mean and the 90^{th} percentile (in parenthesis) from the MC simulations.

Table A2: Magnitude of net emissions (metric tons per year). Negative values represent decreases in emissions from diesel generators over those of the grid.

Country	Metric tons of CO_2/year	Metric tons of $PM_{2.5}$/year	Metric tons of NOx/year	Metric tons of CO/year	Metric tons of SOx/year
Angola	94,200 (29,900-181,000)	280 (90-520)	3,900 (1,200-7,100)	830 (270-1,500)	-1 (-190 – 150)
Cameroon	180,000 (22,000-410,000)	420 (52-930)	5,800 (720-13,000)	1,200 (150-2,800)	100 (-22-310)
Cote d'Ivoire	32,100 (10,500-63,500)	110 (37-210)	1,500 (510-2,900)	320 (110-610)	28 (-15-80)
D.R.C	493,000 (174,000-757,000)	950 (340-1,460)	13,000 (5,000-20,000)	2,900 (1,000-4,400)	600 (210-940)
Ethiopia	63,900 (17,200-132,000)	120 (33-260)	1,700 (460-3,600)	370 (100-770)	78 (21-170)
Ghana	197,000 (70,500-328,000)	490 (180-800)	6,900 (2,600-11,000)	1,500 (550-2,400)	91 (-140-320)
Kenya	52,500 (20,800-85,200)	120 (48-190)	1,700 (680-2,700)	360 (150-580)	-8 (-83 – -49)
Mozambique	18,200 (3,290-40,900)	37 (7-82)	510 (92-1,100)	110 (20-250)	23 (4-50)
Niger	-1,760 (-9,070-4,910,000)	64 (24-98)	860 (320-1,100)	190 (73-300)	-550 (-1,200 – -150)
Nigeria	4,210,000 (1,530,000-6,800,000)	14,000 (5,300-21,000)	190,000 (72,000-280,000)	39,000 (15,000-60,000)	8,800 (3,300-13,000)
Senegal	4,310 (705-10,800)	18 (3-42)	290 (50-630)	63 (11-140)	-58 (-170 – -3)
South Africa	1,030 (-43,800-35,200)	350 (83-750)	4,800 (1,100-10,000)	1,200 (290-2,600)	-1,400 (-2,900 – -400)

Tanzania	40,800 (16,000-59,500)	120 (50-190)	1,700 (700-2,600)	370 (150-560)	-13 (-97-55)
Zambia	38,500 (9,770-80,900)	75 (19-160)	1,100 (260-2,200)	230 (57-480)	40 (10-86)
Zimbabwe	18,600 (3,890-43,100)	100 (27-220)	1,400 (360-2,900)	330 (84-680)	-140 (-300 – -34)

Table A3 summarizes the mean annual air emissions from the grid and the backup generators. We estimated these values by multiplying the appropriate emissions factors and the annual generation from each resource. We have validated the annual CO_2 emissions from the grid using data reported in the WRI CAIT Climate Data Reported, which includes historical annual CO2 emissions from power generation for countries all over the world[146].

Table A3: Annual mean emission from the grid and the backup generators by pollutant by country

Country	CO_2 (metric tons/year)		$PM_{2.5}$ (metric tons/year)		SOx (metric tons/year)		CO (metric tons/year)		NOx (metric tons/year)	
	Grid	Backup Generators	Grid	Backup Generators	Grid	Backup Generators	Grid	Backup Generators	Grid	Backup Generators
Angola	3,440,000	147,000	200	280	12,000	180	1,400	850	5,100	4,000
Cameroon	1,200,000	218,000	150	420	5,200	270	830	1,300	2,800	5,900
Cote d'Ivoire	3,760,000	58,800	350	110	6,200	72	2,700	340	7,600	1,600
D.R.C	8,830	494,000	0	950	9	600	5	2,900	12	13,000
Ethiopia	9,620	64,100	0	120	26	78	4	370	13	1,700
Ghana	3,200,000	261,000	570	500	11,000	320	1,200	1,500	4,700	7,000
Kenya	1,560,000	62,900	510	120	12,000	77	520	360	3,300	1,700
Mozambique	728,000	19,100	13	37	4	23	580	110	1,400	510
Niger	731,000	35,100	83	68	12,000	43	190	200	1,700	940
Nigeria	12,600,000	7,200,000	220	14,000	70	8,800	10,000	42,000	24,000	190,000
Senegal	2,300,000	11,300	1,100	22	24,000	14	680	65	5,700	300
South Africa	253,000,000	212,000	70,000	410	2,000,000	260	24,000	1,200	1,100,000	5,700
Tanzania	2,420,000	66,800	400	130	8,700	81	1,400	390	5,000	1,800
Zambia	260,000	39,400	140	76	3,100	48	69	230	680	1,100
Zimbabwe	6,770,000	57,600	1,300	110	37,000	70	740	330	22,000	1,500

Additional Methods

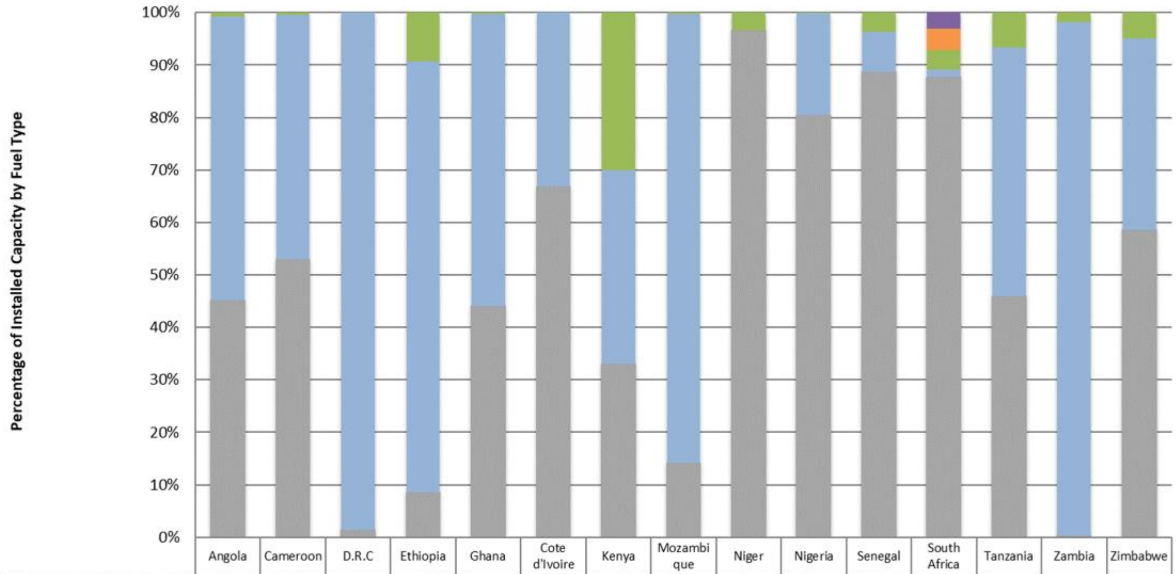
Figure A3 provides the data for electricity capacity and generation in each country in 2014, which we used to derive backup diesel capacity as well as the weighted emissions factors and fuel use. The stacked bar charts represent the (a) composition of each grid by fuel type and (b) generation by fuel type observed in each country. The "other" category, which is present only in South Africa, represents Pumped-Storage Hydro capacity. The table portions of Figure A3 represent the underlying magnitude of power available (a) in GW and (b) TWh generated. All data are for the year of 2014.

Table A4 lists the energy content and conversion values used to calculate input energy for grid level power generation. These data along with the emission factors form the foundation of our analysis.

Table A4: Characteristics of electricity generating fuel.

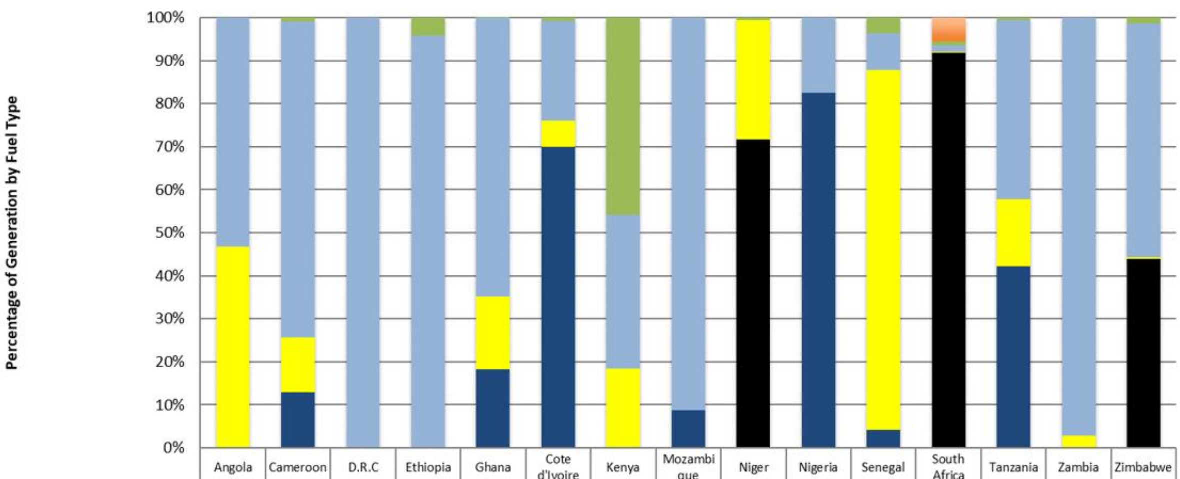
Coal	**Energy Content**	-
Bituminous Coal[147]	27,113 (kJ/kg)	-
Lignite Coal[148]	17, 435 (kJ/kg)	-
Oil Based Products[50]	**Energy Content - HHV (MJ/l)**	**Volume Conversion (metric ton/liter)**
Diesel Fuel	38.7	8.432×10^{-4}
Residual Fuel	41.7	8.432×10^{-4}
Crude Oil	38.5	8.578×10^{-4}

A) Installed Capacity (GW)



	Angola	Cameroon	D.R.C	Ethiopia	Ghana	Cote d'Ivoire	Kenya	Mozambique	Niger	Nigeria	Senegal	South Africa	Tanzania	Zambia	Zimbabwe
Other	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.40	0.00	0.00	0.00
Nuclear	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.86	0.00	0.00	0.00
Non-Hydroelectric Renewables	0.012	0.006	0.00	0.2223	0.008	0.00	0.669	0.007	0.006	0.019	0.035	1.739	0.079	0.042	0.104
Hydroelectricity	0.92	0.721	2.59	1.97	1.58	0.604	0.82	2.187	0	2.04	0.075	0.661	0.562	2.27	0.77
Fossil Fuels	0.77	0.817	0.034	0.204	1.251	1.22	0.734	0.359	0.172	8.418	0.854	40.185	0.546	0.007	1.235

B) Generation(TWh)



	Angola	Cameroon	D.R.C	Ethiopia	Ghana	Cote d'Ivoire	Kenya	Mozambique	Niger	Nigeria	Senegal	South Africa	Tanzania	Zambia	Zimbabwe
Nuclear	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	13.79	0.00	0.00	0.00
Non-Hydroelectric Renewables	0.00	0.07	0.00	0.41	0.00	0.07	4.23	0.00	0.00	0.00	0.13	2.49	0.04	0.00	0.14
Hydroelectricity	5.04	5.07	8.82	9.20	8.39	1.91	3.31	16.18	0.00	5.35	0.32	4.08	2.59	14.04	5.43
Oil	4.44	0.89	0.00	0.01	2.21	0.51	1.71	0.00	0.19	0.00	3.12	0.19	0.96	0.41	0.05
Natural gas	0.00	0.90	0.01	0.00	2.36	5.80	0.00	1.57	0.00	25.04	0.16	0.00	2.63	0.00	0.00
Coal	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.49	0.00	0.00	232.02	0.00	0.00	4.40

Figure A3: Electricity generation data by country. A) Installed generating capacity by country by fuel type in 2014. Data from the Energy Information Administration[149]. B) Electricity generation by country by fuel type in 2014[46].

Emission factors for CO_2 (Table A5) are taken from the IEA CO_2 emissions from fuel combustion-highlights report[44] and are treated for uncertainty. Additional emission factors are subject to uncertainty surrounding plant generating conditions and input fuel quality. The Emission factors from the European Monitoring & Emission Program and the European Enviroment Agency (EMEP/EEA) Emissions Inventory Guidebook[3] provides default emission factors for other non-CO_2 air polluntant that can be used when more specific data are not available. The EMEP/EEA emission factors are derived based on input fuel energy (e.g. GJ of natural gas burned) and are thus not specific to measured emissions in Europe or other areas of the world. We modeled the NOx, CO, SOx, and $PM_{2.5}$ emissions factors using triangular distributions with the given mean as the mode and the 95% confidence interval shown (Table A6) as the lower and upper limits. It is important to note that EMEP/EEA SOx emissions factors for brown coal (lignite), heavy fuel oils (residual and crude oil), and gas oil (light oil) assume no SO_2 abatement while using a mass-based sulfur content. This uncertainty is reflected in the upper bound of SOx emissions distributions, which increases the range of grid SOx emissions observed in our results. If plant level data are available, this uncertainty can be adjusted to reflect applied abatement technology, if any.

Table A5: Power plant emission factors for Carbon Dioxide.

Country	CO_2 (kg/MWh)
Angola	363
Cameroon	173
Cote d'Ivoire	454
D.R.C	1
Ethiopia	1
Ghana	247
Kenya	168
Mozambique	41
Niger	1053
Nigeria	416
Senegal	616
South Africa	1002
Tanzania	389
Zambia	18
Zimbabwe	675

Table A6: Power plant emission factors by fuel type for Non-CO_2 greenhouse gases and criteria pollutants[45].

	95% CI	**NOx (g/GJ)**	**CO (g/GJ)**	**SOx (g/GJ)**	**$PM_{2.5}$ (g/GJ)**
Lignite Coal	Mean	247	8.7	1680	3.2
	Lower	143	6.72	330	7
	Upper	571	60.5	5000	28
Natural Gas	Mean	89	39	0.281	0.89
	Lower	15	20	0.169	0.445
	Upper	185	60	0.393	1.34

Residual Fuel/Crude Oil	Mean	142	15.1	495	19.3
	Lower	70	9.06	146	0.9
	Upper	300	21.1	1,700	90
Light Oil	Mean	65	16.2	46.5	0.8
	Lower	22	4	4.65	0.3
	Upper	195	65	465	2.5

Table A6 does not include information for bituminous coal, which is widely used for power generation in South Africa and Zimbabwe (See Figure A2b). The NOx, SOx, and $PM_{2.5}$ emission factors for bituminous coal are taken from estimates of South African coal generation because country-level data are available[150]. Note that these data did not include estimates for CO so default emission factors are used for this pollutant. We assume Zimbabwe's bituminous coal shares similar characteristics to South Africa's coal. Table A7 lists the emission factors for Bituminous coal electricity generation. The mean value is taken as an estimate of 2012 emission factors in South Africa and the confidence interval bounds correspond to projected estimates of best-case and worst-case emissions (as a percentage decrease and increase, respectively, over 2015 emission levels)[150].

Table A7: Bituminous coal power plant emission factors by fuel type for Non-CO2 greenhouse gases and criteria pollutants.

	95% CI	**NOx**[150] **(kg/MWh)**	**CO**[45] **(g/GJ)**	**SOx**[150] **(kg/MWh)**	**$PM_{2.5}$**[150] **(kg/MWh)**
Bituminous Coal	Mean	4.5	8.7	8	0.3
	Lower	4.05	6.15	6	0.18
	Upper	6.3	15	11.2	0.42

Table A8 summarizes the emission factors for diesel generators, which are taken from the literature[39,47]. To model the efficiency of the backup generators, we use a triangular distribution assuming a lower bound of 20% (heat rate of 17,000 BTU/kWh), the upper bound of 35%[39] (heat rate of 9750 BTU/kWh), and a mode of 25%[48]. The available backup capacity is expressed as a percentage of each country's central grid capacity, as summarized in Table A9[34].

Table A8: Diesel Generator Emission Factors. Emissions of $PM_{2.5}$ which are adapted from Gilmore et al (2010)[39] while NOx, CO, SOx, and CO_2 are adapted from the U.S. EPA[47].

Pollutant[39,47]	Emission Factor (kg/MJ)
$PM_{2.5}$	1.361×10^{-4}
NOx	1.896×10^{-3}
CO	4.084×10^{-4}
SOx	8.598×10^{-5}
CO_2	.071

Table A9: Distribution of Diesel Generator capacity as percentage of installed grid capacity[34]. These values represent the percentage of load replaced in our analysis.

Country	Mode	Min	Max
Angola	8%	1%	25%
Cameroon	1%	1%	51%
Cote d'Ivoire	6%	1%	22%
D.R.C	46%	1%	51%
Ethiopia	1%	1%	12%
Ghana	12%	1%	22%
Kenya	7%	1%	12%
Mozambique	1%	1%	25%
Niger	20%	1%	22%
Nigeria	22%	1%	22%
Senegal	1%	1%	25%
South Africa	2.5%	1%	25%
Tanzania	12%	1%	12%

Zambia	3%	1%	25%
Zimbabwe	5%	1%	25%

Finally, Table A10 summarizes information on diesel and electricity prices in each country (2014 US dollars). The grid prices presented are the average costs based on tariffs for residential, commercial, and industry consumers[51,52].

Table A3: Diesel prices and electricity tariffs by country. The range of diesel generator costs correspond to the fuel consumption observed in our Monte Carlo Analysis. All values in US$$_{2014}$.

Country	Diesel Price ($/liter)	Cost of diesel generator electricity ($/kWh)			Price of grid electricity ($/kWh)
		Mean	5%	95%	
Angola	$ 0.51	$ 0.19	$ 0.15	$ 0.22	$ 0.05
Cameroon	$ 1.14	$ 0.42	$ 0.34	$ 0.50	$ 0.12
Cote d'Ivoire	$ 1.17	$ 0.43	$ 0.35	$ 0.51	$ 0.13
D.R.C	$ 1.67	$ 0.61	$ 0.50	$ 0.73	$ 0.12
Ethiopia	$ 0.89	$ 0.33	$ 0.27	$ 0.39	$ 0.04
Ghana	$ 1.03	$ 0.38	$ 0.31	$ 0.45	$ 0.11
Kenya	$ 1.07	$ 0.39	$ 0.32	$ 0.47	$ 0.15
Mozambique	$ 1.20	$ 0.44	$ 0.36	$ 0.52	$ 0.08
Niger	$ 1.03	$ 0.38	$ 0.31	$ 0.45	$ 0.17
Nigeria	$ 0.84	$ 0.31	$ 0.25	$ 0.37	$ 0.09
Senegal	$ 1.51	$ 0.56	$ 0.45	$ 0.66	$ 0.23
South Africa	$ 1.17	$ 0.43	$ 0.35	$ 0.51	$ 0.06
Tanzania	$ 1.20	$ 0.44	$ 0.36	$ 0.52	$ 0.15
Zambia	$ 1.59	$ 0.59	$ 0.47	$ 0.69	$ 0.06
Zimbabwe	$ 1.48	$ 0.54	$ 0.44	$ 0.64	$ 0.09

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