The Dirty Footprint of the Broken Grid

The Impacts of Fossil Fuel Back-up Generators in Developing Countries

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FORWARD AND ACKNOWLEDGEMENTS

The following research models the global fleet of back-up fossil fuel generators. It is part of IFC's emerging work to support solar and energy storage solutions that can provide reliable, sustainable, affordable energy to people and businesses relying on fossil fuel generators.

The research findings include estimates of fleet size, composition, energy service, fuel consumption, and resulting financial costs and pollutant output (pollutant emissions) as an indicator for health and climate impacts. Our modeling focused on understanding global and regional trends to help clarify the overall footprint and related opportunity for alternative solutions. It applied a broad geographic scope including 167 developing countries (excluding China).

We limited our view to this scope and did not account for non-fuel maintenance costs, nor estimate the value of lost productivity from generator downtime and management, or costs passed onto customers from enterprises reliant on generators for day to day operations. We only present the part of the picture that we felt we could reasonably estimate with available data from multiple sources. We rely on official import/export data, and therefore do not account for generators imported unofficially or produced locally. The available data for generator performance typically comes from laboratory testing, which would likely underestimate fuel use and emissions for generators in use on the ground. Overall, the estimates presented in this summary are conservative, we believe significantly so.

This is the foundation piece of an open source resource that we hope becomes a broader collaborative effort at producing and sharing data. Because of our global focus and standardized approach to modeling, the specific results should be treated as a starting point for further research, rather than a final result. Focused work in national and local markets will be crucial to follow through on this first effort.

This is the impressionistic painting. We hope it leads to a more detailed and fuller picture.

We would like to acknowledge and thank our research partner, the Schatz Energy Research Center at Humboldt State University. This research and IFC's engagement in this area will be further developed in partnership with the IKEA Foundation, Netherlands Ministry of Foreign Affairs and the Italian Ministry of Environment, Land and Sea.

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Executive Summary

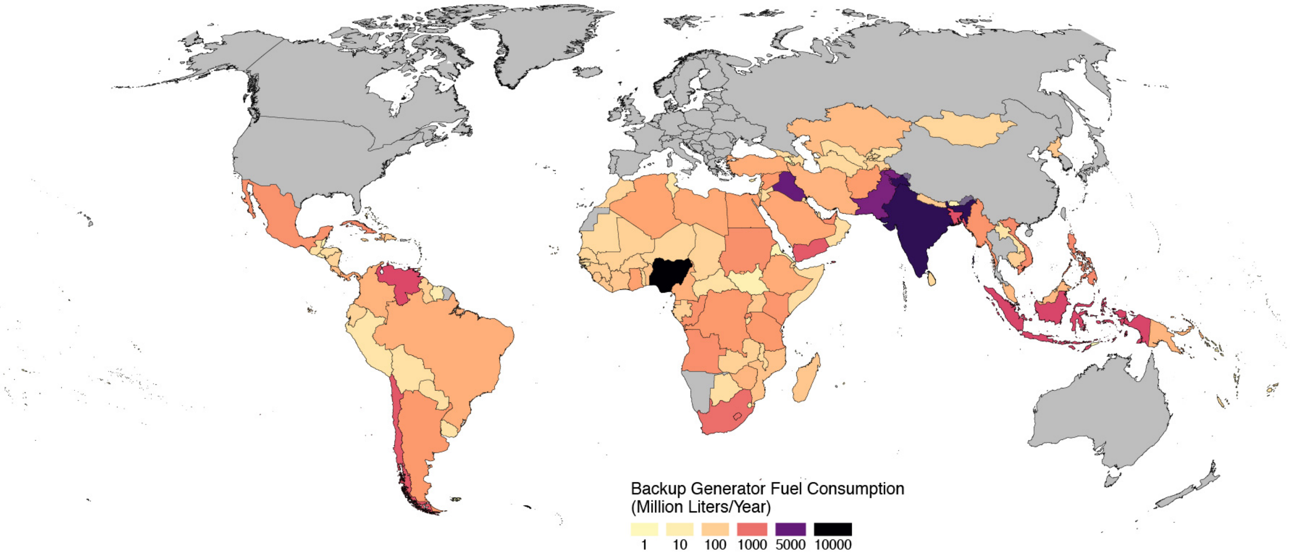
About 1.5 billion people around the world live day-to-day with "broken" electricity grids and experience blackouts for hundreds and sometimes thousands of hours a year. For this population, reliance on distributed diesel and gasoline backup generators, or BUGS, is a common stopgap measure. These generators are deployed across the globe on a large scale both on- and off-grid, at homes, businesses, and industrial sites. They support access to energy but come with significant costs.

The goal of this research project is to estimate the scale and impacts of generators serving energy access needs within developing regions of the world. With a broad geographic scope, including 167 developing countries (excluding China), the coverage represents 94 percent of the population living in low- and middle-income regions of the world.. We develop and use a modeling framework using the best available data for each country to estimate the size and composition of the fleet of generators, operational time, fuel consumption, and financial, health, and climate impacts. The estimates are designed to help clarify the opportunity in developing countries for clean technologies such as solar and storage (solar + storage) to replace generators, and to avoid these costs and impacts.

Major Findings

The fleet of generators in the developing countries modeled serves 20 to 30 million sites with an installed capacity of 350 to 500 gigawatts (GW), equivalent to 700 to 1000 large coal power stations. The fleet has a replacement value of $70 billion and about $7 billion in annual equipment investment. Over 75 percent of the sites where generators are deployed are "grid-connected." The map in **Figure 1.1** illustrates the volume of diesel and gasoline fuel burned annually across modeled countries.

FIGURE 1.1: TOTAL DIESEL AND GASOLINE CONSUMED IN 2016 ACROSS ALL MODELED COUNTRIES.



Backup generators are a major source of electricity access in some developing regions, providing 9 percent of the electricity consumed in Sub-Saharan Africa, and 2 percent in South Asia. In western Africa, generators account for over 40 percent of the electricity consumed annually. This requires considerable quantities of fossil fuel; 20 percent of the gasoline and diesel consumed in Sub-Saharan Africa is burned for electricity generation. In regions where generators are a predominant source of energy access, spending on fuel can be equivalent to or higher than the total national spending on the grid. **Figure 1.2** shows how the spending is notably similar in size to the overall utility electricity sector in some regions of Africa. Western Africa is a particularly significant market for backup generators, owing largely to Nigeria, with its large economy, population, and low-reliability power sector that together drive many homes and businesses to rely on backup generators.

Electricity from backup generators is expensive, with \$28 billion to \$50 billion spent by generator users on fuel each year. This corresponds to an average service cost of \$0.30/kWh for the fuel alone (ranging from \$0.20/kWh to \$0.60/kWh depending on generator size and fuel type), usually much higher than the cost of grid-based energy (\$0.10–0.30 / kWh) and on par with current estimates of the levelized cost of solar + storage.[1] Operations and maintenance costs for generators could add an additional 10 percent to 20 percent to fuel service costs.[2]

Backup generators are a significant source of air pollutants that negatively impacts health and the environment. As a pollution source, generators are often hidden from policymakers since their fuel consumption may be lumped in with the transport sector in official statistics. Generators consume the same fuels and also emit the same pollutants as cars and trucks, except they are used in closer proximity to people's homes and businesses. Often, emission limits for generators are also less stringent than for vehicles. As a result, the pollutants emitted from generators may represent meaningful but largely unaccounted or misclassified impacts on population health and the environment. . Generators emit the same pollutants as cars and trucks, except they are used in closer proximity to people's homes and businesses, and emission limits are often less stringent than for vehicles. In Sub-Saharan Africa, we estimate that generators account for the majority of power sector emissions of nitrogen oxides (NO_x) and fine particulate matter ($PM_{2.5}$), with their contribution to $PM_{2.5}$ being equivalent to 35 percent of the emissions from the entire transportation sector. BUGS are a modest contributor to CO_2, accounting for roughly 1 percent of annual emissions across modeled countries.

FIGURE 1.2: ANNUAL EXPENDITURE ON GRID-BASED ELECTRICITY VS. FUEL FOR BACKUP GENERATORS BY REGION, AND THE TOTAL INSTALLED FLEET CAPACITY, IN AFRICA

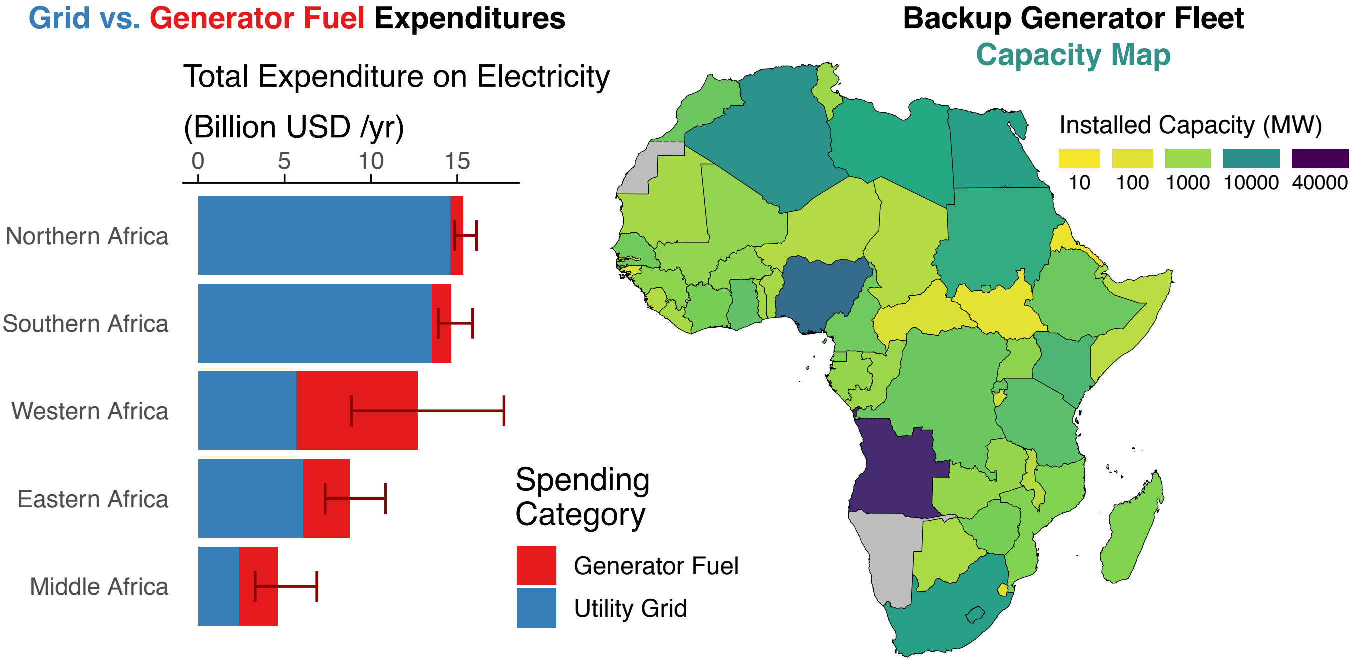


FIGURE 1.3: A CLUSTER OF SMALL GASOLINE GENERATORS LEAKING FUEL AND LUBRICATING OIL INTO A STORMWATER TRENCH IN A MARKET IN ABUJA, NIGERIA

Photo: A. Jacobson

Our modeling focused on understanding global and regional characteristics to help clarify the overall opportunity. It is important to emphasize the need for focused work in national and local markets to follow through and solidify the market intelligence groundwork. Because of our global focus and standardized approach to modeling, the specific results for every one of the 167 countries we included in the modelling effort should be treated as a starting point for further insight, rather than a final result. Despite the negative impacts that unreliable electricity supply has on populations and economies, there remains limited data on power systems and the operational characteristics of BUGS fleets in specific developing country contexts, and significant discrepancies exist in coverage and reporting which make comparison across what few data sets exist difficult. In addition, there are gaps in our ability to estimate the scale of unregulated sales of generators and a weak understanding of the true cost of operations and maintenance, including lost opportunities for productivity.

When interpreting our analysis, it is important to keep these tradeoffs and assumptions in mind. During the model development our priority was to use a consistent methodology for estimating fleet characteristics across countries with comparable data sources whenever possible. We chose not to include “expert based” estimates for sectors or countries with missing data. The estimates we make are benchmarked against national and regional fossil fuel inventories as an additional verification step. Based on these decision factors and known data gaps, our central estimates of fleet characteristics are likely conservatively low and could be treated as a reasonable lower bound.

Reported fleet sizes and impacts could be underestimated for the following reasons (among others):

- **Gray market or untracked imports of generators.** Generators that are missed by formal tracking are not counted in the import / export data that we used as the basis for fleet size in most countries.
- **Locally assembled generators.** Most generators are assembled in industrial centers in Asia, but domestically assembled units may be missing from our data.
- **Longer generator lifetimes.** It is possible that generators in some areas are maintained to run beyond the assump-

tions we make about lifetime. This would lead to our estimates of active fleet size to be conservatively low.

- **Very poorly performing/high pollution generators.** Based on the available data, we apply performance values from generators measured in developed countries, typically under controlled laboratory settings. We expect this to lead to conservatively low estimates of fuel demand and related impacts compared to poorly performing generators that may be in use.

Regardless, the results are still significant and large—and the reality that could be uncovered with more detailed understanding of local markets could be even larger.

Next Steps

Overall, **our results indicate a significant opportunity to reduce costs and negative health and environmental externalities by replacing diesel and gasoline generators.** To follow through, it is important to develop both the technology and business model solutions needed and to improve the understanding of generator impacts in local contexts. The local realities of the solar industry, grid reliability, fossil fuel competitiveness, and the utility and regulatory approach to distributed generation are among the important factors. While our modeling approach was not designed to reveal special insight on how to deploy such clean technologies, there are some clear next steps that could be taken.

First, development and private sector actors should work to **accelerate and support emerging clean energy technology deployment and markets** to better serve the needs of people who now rely on generators. In parallel with market transformation, **improving the fidelity of data and knowledge** on generators could help focus and target these efforts.

Our initial results suggest that a large opportunity exists, but that there is still significant uncertainty in many facets of our estimates that could affect local decision making. Improving understanding of backup generators could help eliminate them. The uncertainty decomposition technique we used in our model reveals where additional research could contribute most to improving understanding of the fleet, operations, and impacts of generators. We found that for gasoline generators, about 60 percent of uncertainty is related to the number of sites using generators, due to poor understanding of the service life of these relatively small and inexpensive generators. Targeted research and better survey coverage of homes and businesses, including more detailed data on service quality using instruments like the World Bank Multi-Tier Framework surveys, could significantly improve certainty in the estimates related to gasoline generators. For diesel generators, about 60 percent of the uncertainty is related to the sizing of the fleet of diesel generators and the loads they serve. For these, a detailed survey of sites, including monitoring of loading and fuel consumption, could help address this uncertainty. For all classes of generators, data on the frequency, duration, and patterns of blackouts contributes to 10 percent to 20 percent of the uncertainty in estimates. Grid status data could limit this uncertainty and also help inform the design of clean technologies such as solar and storage that would serve needs of customers facing particular reliability realities.

There are also **remaining areas of missing fundamental data related to the emissions from backup generators and their impacts on community health and air quality.** There is a scarcity of data on the performance of generators used in developing countries. This has led to a reliance on performance data from well-maintained generators that are very likely to be better performing than the units deployed in countries modeled in our study. Furthermore, the exposure contribution to people is not well mapped or understood, nor are the resulting health impacts. If generators follow similar trends to other energy service technologies, **our results likely lead to highly conservative estimates of emission impacts.** Making measurements of emissions from generators operating in practice is a high priority to better understand the health and environmental benefits from relegating or replacing fuel-based generators.

Glossary

TERM (SYNONYM / ABBREVIATION)	DEFINITION
BC	Black carbon
BUGS	Backup fossil-fueled generator
Capacity factor	Fraction of rated capacity that the generator operates at
CIA	United States Central Intelligence Agency
CO_2	Carbon dioxide
EID	Experienced interruption duration
ER	Emission rate; the quantity of pollutant released to the atmosphere per unit of time
EF	Emission factor; the quantity of pollutant released to the atmosphere per unit of activity associated with that release
GAINS	Greenhouse Gas - Air Pollution Interaction and Synergies Model
GBD	Global burden of disease
GDP	Gross domestic product
GEE	Generalized estimating equation
Generator: diesel large	Diesel-fueled generator with a rated capacity greater than 300 kW
Generator: diesel small	Diesel-fueled generator with a rated capacity of less than 60 kW
Generator: petrol or gasoline	Petrol-fueled generator (any rated capacity)
Generator: diesel medium	Diesel-fueled generator with a rated capacity of between 60 and 300 kW
GW	Gigawatt
IEA	International Energy Agency
IFC	International Finance Corporation
IIASA	International Institute of Applied Systems Analysis
IMF	International Monetary Fund
kt	Kiloton
kVa	Kilo-volt-ampere
kW	Kilowatt

kWh	Kilowatt hour
LMICs	Low- and middle-income countries (World Bank, 2018)
MJ	Megajoule
Mt	Megaton
MW	Megawatt
NMVOC	Non-methane volatile organic compounds
NOX	Nitrogen oxides
O&M	Operation and maintenance
O3	Ozone
OC	Organic carbon
PM2.5	Particulate matter with a diameter of 2.5 micrometer or less
Pollutant concentration	Mass of pollutant contained per unit volume of media
PPP	Purchasing power parity
PV	Photovoltaics—A type of solar electricity technology. The typical technology used for "solar panels" that are installed on buildings and in utility-scale generation.
Rated capacity/ nameplate capacity	Intended full-load sustained output of a generator (nameplate capacity)
Runtime	Duration of time a generator is running over a specified time period
SAIDI	System average interruption duration index
SE4ALL	Sustainable Energy for All
SLCFs	Short lived climate forcers
SO2	Sulfur dioxid
solar+storage	An energy system combining distributed solar electricity generation with battery energy storage, often with the capability to operate and serve on-site loads without the grid.
TWh	Terawatt hours (10^12 watts)
UI	Uncertainty interval
UN	United Nations
USD	United States dollar
UV	Ultraviolet
VOC	Volatile organic compounds

Introduction

Living with an unreliable electricity connection is a day-to-day reality for billions of people in developing countries. Blackouts can be regular or unexpected, stretching to hours or days.

To better meet their energy needs, tens of millions of people purchase and operate distributed generation to supplement their unreliable grid connection at households and businesses, or for off-grid power. For decades the only viable option has been fossil fuel "backup" generator sets (BUGS) like the one pictured here.[3] These generators are usually designed for intermittent service but are used for thousands of hours a year in places with the worst grid reliability or in off-grid locations. Continued reliance on them brings financial, environmental, and health hardships.

Photo: A. Jacobson

Reducing reliance on BUGS through replacement with integrated solar and energy storage systems presents an opportunity to reduce these hardships. However, understanding the scale of this opportunity requires an understanding of the extent of their use and the impacts of their operation. Because of the distributed and untracked nature of BUGS, however, there has been limited or incomplete information available around the current impacts of BUGS and the level of energy service they provide. This study contributes to addressing this knowledge gap by performing the most detailed characterization to date of backup generator fleets, the cost of their operation, and their contribution to health and climate damaging pollutant emissions.

We use existing data to model the fleets and operations of BUGS in 167 developing countries,[4] addressing several questions:

- How many generators are installed and at what size range?
- What are the patterns of grid (un)reliability that drive generator use?
- How much energy service do generators provide?
- How much fuel is burned and at what welfare and environmental cost?
- What are the major knowledge gaps affecting our understanding of generator operations and impacts?

This report describes our approach and results, which address the questions above. The results reveal the vast scale of reliance on BUGS.

Background and Research Methods

COPING WITH BROKEN GRIDS

People use fossil fuel BUGS primarily because of an inability to access reliable electricity service from an area electric power system (i.e., the grid). This access gap can stem from an inability to make physical connection to the grid or from intermittent grid service. For many, grid outages are a part of everyday life. The duration and frequency of such outages varies widely across countries and time of year depending on demand and the availability of energy sources needed to generate electricity.

The reliability of power systems also varies, from highly stable and reliable grids to power systems with frequent rolling or unplanned blackouts that can stretch for hours or days. Surveys conducted by the World Bank indicate that the duration of outages (often measured in terms of the System Average Interruption Duration Index, or SAIDI) ranges from hundreds to thousands of hours annually in countries with weak grids.[5] Based on published SAIDI estimates, we estimate that more than 2 billion people live with blackouts more than 100 hours a year and 1 billion with more than 1,000 hours.

PRIMER ON BACKUP GENERATORS

In response to uncertain grid conditions, backup generators—while only a stop-gap measure—have the potential to impose significant monetary and non-monetary costs on users, communities, businesses, and the environment. This background section briefly describes some background information on generators and their operation, followed by an overview of the methods we used to estimate them. In Appendix 1 we provide more depth and details on the background and methods.

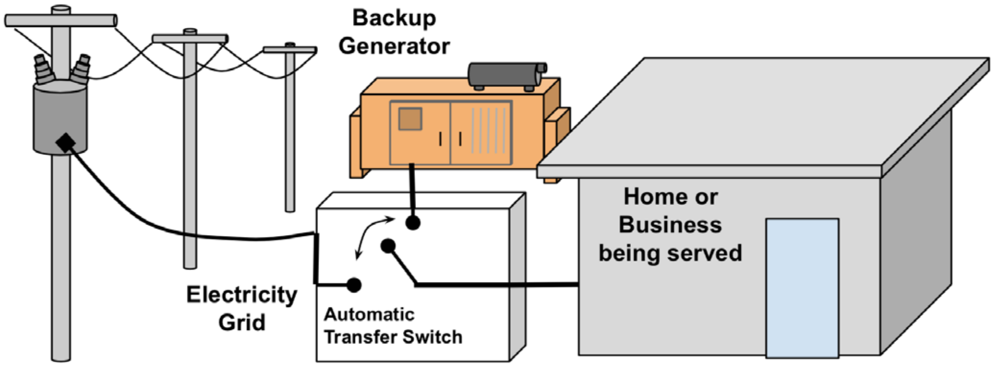
Generator Types

There is a vast range in generator scales serving sites across the world, from less than a kilowatt to several megawatts, powering sites ranging from small households to industrial facilities. Understanding the size of these segments is important for evaluating the scale of the opportunity to replace generators. For smaller systems, a more standardized approach may be appropriate, while for larger generators there could be a business case for more customized design.

Generators are typically installed so that they run as standalone alternatives to the grid or operate as an alternative power source during grid outages. **Figure 3.1** illustrates a typical arrangement for grid-connected sites that use a transfer switch (often automated to switch on during blackouts) to connect the loads at a home or business to the grid or to a generator. Some sites do not use automatic transfer switches, instead relying on more manual, less intrinsically safe methods for powering loads in parallel with the electricity grid.

We distinguish generators by the fuel they run on (diesel vs. gasoline) and the amount of power they can generate (watts). Both factors affect the efficiency of electricity generation and the size of applications. It

FIGURE 3.1: OUTLINE OF A SAFELY INSTALLED BACKUP GENERATOR INSTALLATION USING A TRANSFER SWITCH (NOT TO SCALE) TO ISOLATE THE GENERATOR AND HOME OR BUSINESS BEING SERVED FROM THE REGIONAL GRID



is important to note that direct drive generating units for agricultural and industrial applications are not considered in our fleet or impact estimates.

The Many Costs of Generators

The continued reliance and operation of BUGS impose a variety of costs on users, communities, governments, and the environment; we distinguish and examine some of these costs as impacts within our modeling framework.

The costs to users include:

- Capital costs to purchase and install a generator (estimated based on import value and retail markup)
- Fuel costs to operate the generator (based on expected runtime due to grid outage)
- Operation and Maintenance (O&M) costs are not included as a cost in our model estimates but can be considerable in some BUGS applications—conservatively on the order of 10 percent to 20 percent of the fuel costs in most situations.[6]

Indirect costs

In addition to direct costs related to fuel, replacement parts, and technician labor, the effort spent to operate, maintain, and cope with generators imposes an opportunity cost on users. Depending on the frequency of use, purchasing fuel and refueling the generator can be a daily or more frequent chore that exposes people to harmful fumes and spilled fuel, and may require considerable travel and transportation costs to refill containers. The time spent managing a generator is lost to other valuable activities. For business operators, this means less time to focus on core income-generating activities. For households, this means less time to focus on family, leisure, and producing a household income. These additional costs of operation are not included in our estimates due to a lack of supporting data and knowledge beyond anecdote. They present additional opportunities to provide value to people who replace generators with less burdensome pathways to electricity access.

Subsidies and public costs

The use of BUGS to meet energy service needs is often incentivized and enabled through government subsidies on fossil fuels. Despite the well-intentioned goals of many subsidy schemes, they are often inefficient and incur direct and indirect costs to users, governments, and the environment. These subsidies make alternative pathways to electricity services less competitive by creating artificially low service costs for BUGS.

Reducing reliance on generators could ease the subsidy burden on government budgets, while removing or reducing subsidies could better signal the cost of backup generation to customers who may have other options.

Air Pollution

BUGS are a potentially significant pollutant source, especially at a local level. In areas where they are deployed, BUGS contribute to the emissions of health and climate damaging pollution. The emissions from BUGS contribute directly or indirectly to nearly all pollutants found on major priority (criteria) pollutant lists developed for the protection of human health. BUGS also contribute to climate change through their emissions of carbon dioxide and numerous short lived climate forcing pollutants (SLCFs).

Community Disruption

Noise pollution and accidental injuries are important impacts of BUGS, especially at the local level, but were not examined in detail as part of this study. Exposure to excessive noise contributes to the local burden of disease through increased risk of heart disease, cognitive impairment in children, and loss of sleep, among others. BUGS are also disruptive to social and business activities and are a frequently mentioned nuisance in accounts from people who live with them.

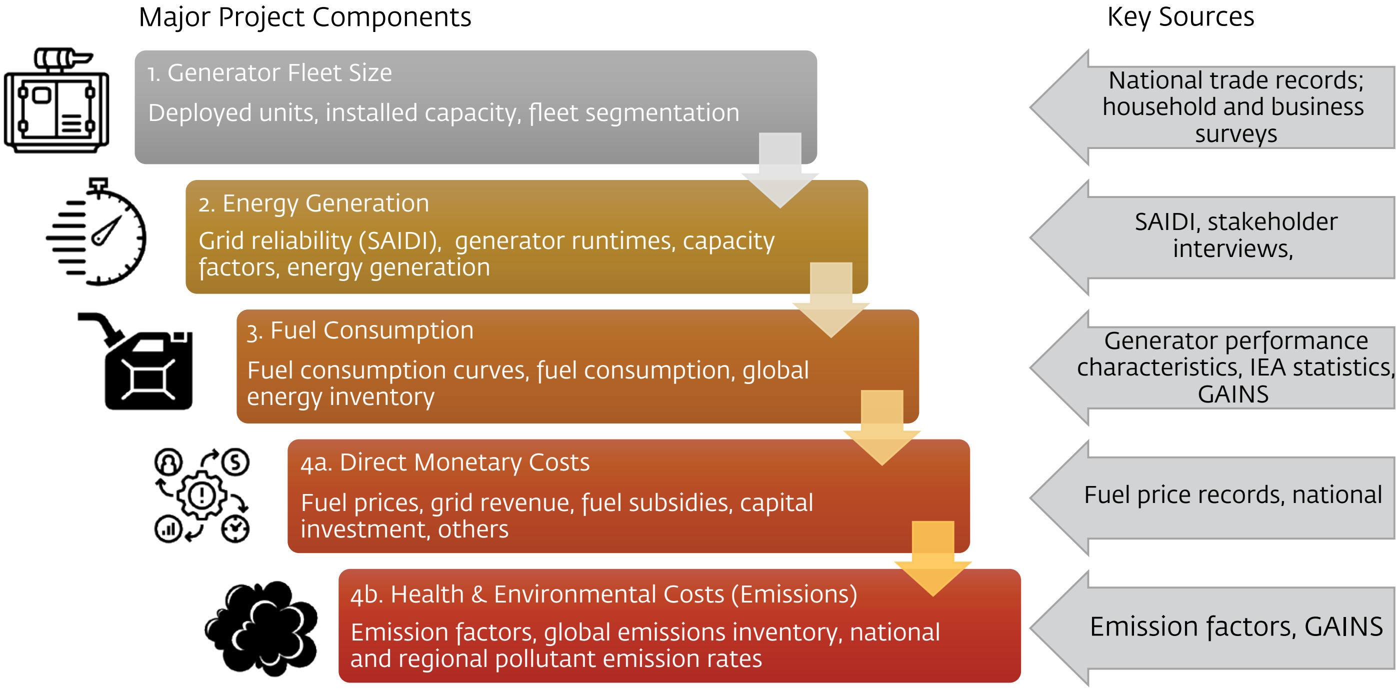
RESEARCH METHODS OVERVIEW

This study characterizes backup generator operations in 167 countries, representing 94 percent of the population living in low- and middle-income regions of the world, excluding China. For most countries we applied a standardized approach for modeling the backup generator sector based on globally available data sets. For Nigeria and India (the top two markets in terms of total load served by generators) a more customized approach was taken to improve user segmentation and improve the model fidelity.

Figure 3.2 shows the workflow and types of data sources used to support our estimates, including:

1. Global import/export trade data on generators and national surveys were used to estimate the number of generators used in 167 developing countries (fleet size), classified by fuel type (i.e., diesel, gasoline) and size (maximum power output) categories. In most countries (except India and Nigeria) we did not attempt to account for domestically produced generators, which is a known source of conservative bias in our approach.
2. The total duration of power outages (i.e., system average interruption duration index, or SAIDI) was the basis for the **hours of BUGS operation (runtime);** this was combined with manufacturer data about their **efficiency and assumptions about loading factor** of generators to estimate energy generation and fuel consumption.
3. Fuel consumption results were used to update a widely used fuel and emissions inventory in order to estimate the contribution of BUGS to fossil fuel demand and emissions of health and climate damaging pollutants.[7] Fuel estimates were compared to IEA statistics for the power and commercial sector and adjusted so that the overall energy use is consistent with IEA.
4. These fuel consumption quantities are used to estimate fuel-related costs and pollutant emissions:
    - a. Fuel cost based on consumption and estimated retail prices
    - b. Cost of subsidizing fuel for BUGS based on estimated consumption subsidies
    - c. Pollutant emissions from available data for generator performance.

FIGURE 3.2: OVERVIEW OF MAJOR PROJECT COMPONENTS, MODEL FLOW-DOWN, AND KEY DATA SOURCES



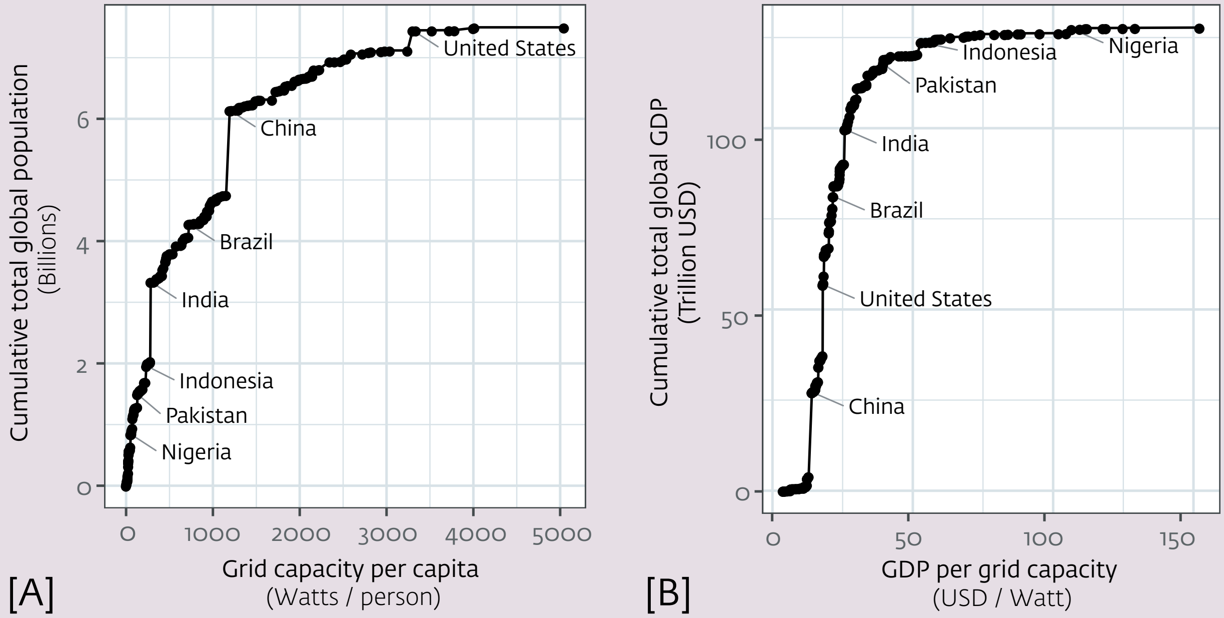
We consider the uncertainty of input data in our reporting of results. Our modeling approach uses Monte Carlo simulations to randomly vary uncertain parameters (like the number of hours of blackout or generator capacity) within reasoned boundaries to estimate a range of possible outcomes. In the results we use error bars and ranges that contain 90 percent of the possible cases we estimated. We also performed a more in-depth uncertainty decomposition to identify the biggest sources of error in our model, with details described in Appendix 2.

Nigeria: a unique and large-scale backup generator market

Nigeria is a notoriously large market for backup generators. While it has the largest population (200 million people) and economy ($1.1 trillion GDP PPP adjusted) in Africa,[8] there are only 5.3 GW of large-scale power stations reliably connected to the regional grid,[9] which is 10 percent of the capacity of South Africa (with 55 million people and $0.767 trillion GDP PPP adjusted). This installed power capacity amounts to about 30 Watts per person, a similar installed capacity per capita to Ethiopia, Afghanistan, and the Democratic Republic of the Congo (DRC). As a point of reference, the global *average* is about 900 Watts per person. Figure 3.3 below shows that, compared to other large countries in the world, Nigeria is among the lowest per capita for generation capacity on the grid. However, Nigeria also has nearly the highest level of economic output in terms of GDP per installed watt of grid-scale generation, at over $100/Watt.

The grid in Nigeria is not sufficient to serve the needs of the country, and the massive population and economy of Nigeria is instead largely powered with electricity from small-scale generators.

FIGURE 3.3: GRID GENERATION CAPACITY IN THE CONTEXT OF COUNTRY POPULATION AND ECONOMY SIZE



Labels are included for the seven countries with 200 million people or more. Panel [A] shows generators per capita. Panel [B] shows economic production in terms of GDP per installed watt of grid generator capacity. The source data are from CIA World Factbook,[10] with a modification of Nigeria generation capacity data based on an SE4All prospectus.[11]

FIGURE 3.4: DIESEL GENERATORS TYPICAL OF THOSE THAT POWER LARGE HOUSING, COMMERCIAL, AND INSTITUTIONAL BUILDINGS

Photo: A. Jacobson
In the background is a solar street lamp and a presumably low-reliability electric distribution circuit.

The "backup" generators deployed in Nigeria include both diesel units and smaller gasoline-powered generators. Large diesel generators power offices, industry, and large homes and businesses (as is common in many parts of the world with poor or no electricity access). The cost to operate these large generators is significant. A recent estimate by the Nigeria Labor Congress shows that "as much as N3.5 tn" (approximately $17 billion USD) is spent each year by industrial generator users.[12] The generators are also used at institutional, commercial, and large housing sites, like the one pictured in **Figure 3.4.**

There are many large diesel generators in Nigeria, but the country is also well known for widespread use of small gasoline generators. These inexpensive units have become newly available and emerged in recent years as a fast-growing segment. Many are two-stroke generators that burn a mixture of gasoline and lubricating oil (as opposed to quieter and typically less polluting four-stroke engines like those used in cars). In popular culture, this category of generator is known as, "I better pass my neighbor." Units have proliferated across households and small businesses and were later banned from import in large quantities by the government in 2015 over concerns about local air pollution.[13] In spite of the ban, these units remain widely available in retail markets. Two images below illustrate the ubiquity of these generators. Both show how merchants and small businesses in the market rely on generators for power in Abuja, Nigeria.

The preponderance of generators in Nigeria is both an economic and health burden. In our modeling study we are able to estimate capital expenses, fuel costs, and air pollution quantities, but the effect of generator operation on quality of life is best understood through testimonials from people who live with them.

On economic burdens: "Without electricity, no nation can go ahead. Without electricity there is nothing that is happening in the country. So we need power. … Three or four days there will be a power supply. The next day off, the next three days on. That is the challenge we are having now."[14] The generators in use also impose a significant burden of effort and cost for operations and maintenance. As one shopkeeper described, "I have three generators.

FIGURE 3.5: SMALL GASOLINE GENERATORS POWERING SHOPS IN AN ABUJA MARKET

Photo: A. Jacobson

FIGURE 3.6: GENERATORS LINE THE STREET IN A MARKET IN ABUJA

Photo: A. Jacobson

Sometimes when one is spoiled I take it to the mechanic. When the second one spoils I take it to the mechanic."

Air pollution and the cacophony of ambient noise from generators is top of mind for people who live with them as well. One shop owner interviewed in Abuja explained that, "Everything about generators is not good. Because number one, noise! … You cannot hear well anywhere. … The smoke causes a lot of sickness in the body. It is not good for human beings."[15]

The marketplace has begun to respond to the emerging opportunity presented by reliable, economic, safer, and quieter solar and storage options. An investment prospectus for Nigeria's Solar Energy for All (SE4ALL) efforts described a pipeline of over 20 projects incorporating clean energy. The description for one of them crystallizes the opportunity to replace burdensome generators with solar[16]:

> "Over reliance on gasoline generators and its attendant high cost of maintenance leads to the failure of many small scale enterprise (SSE) start-ups in Nigeria. It also leads to low return on investment for those with forbearance to survive among these enterprises. It also has negative impacts on the work environment in terms of noise and pollution, contributing to climate change due to CO_2 emissions. This is despite the fact that their quantum [of] energy demand can be met by an alternative low cost source of energy—Solar PV as the most feasible."
>
> —*Project Description from SE4ALL Prospectus*

Results

THE GLOBAL FLEET OF BACKUP GENERATORS

Fleet Size & Composition

The global fleet of BUGS is substantial and underscores the potential burden resulting from poor service quality. We estimate that 25 million generators (90 percent UI: 10 to 40 million units) were deployed in 2016 within developing countries (**Figure 4.1**).[17] Nineteen million units, or 75 percent of the global fleet, are operated at sites with grid connection, reflecting the fact that the need for generators often results from weak or broken grids rather than a lack of grid connection.

The global backup generator fleet is dominated in numbers by small gasoline and diesel generating units that provide service for loads less than 60 kW. Nearly 20 million small gasoline generators are currently deployed across modeled countries, accounting for over three quarters of the global fleet. Five million small diesel generators (< 60 kW) are currently deployed, accounting for 20 percent of the global fleet and the majority of diesel backup units. Medium (60 to 300 kW) and Large (> 300 kW) sized diesel generators together account for around 2 percent of the global fleet and 10 percent of diesel generating sets (0.5 million units). The largest regional fleets exist in South Asia (3.4 million), Sub-Saharan Africa (6.5 million), and the Middle East and North Africa (5.3 million), with generator compositions similar to that of the fleet across all modeled countries (**Figure 4.2**).

FIGURE 4.1: BACKUP GENERATOR FLEET COUNT ESTIMATES FOR 2016 ACROSS ALL MODELED COUNTRIES

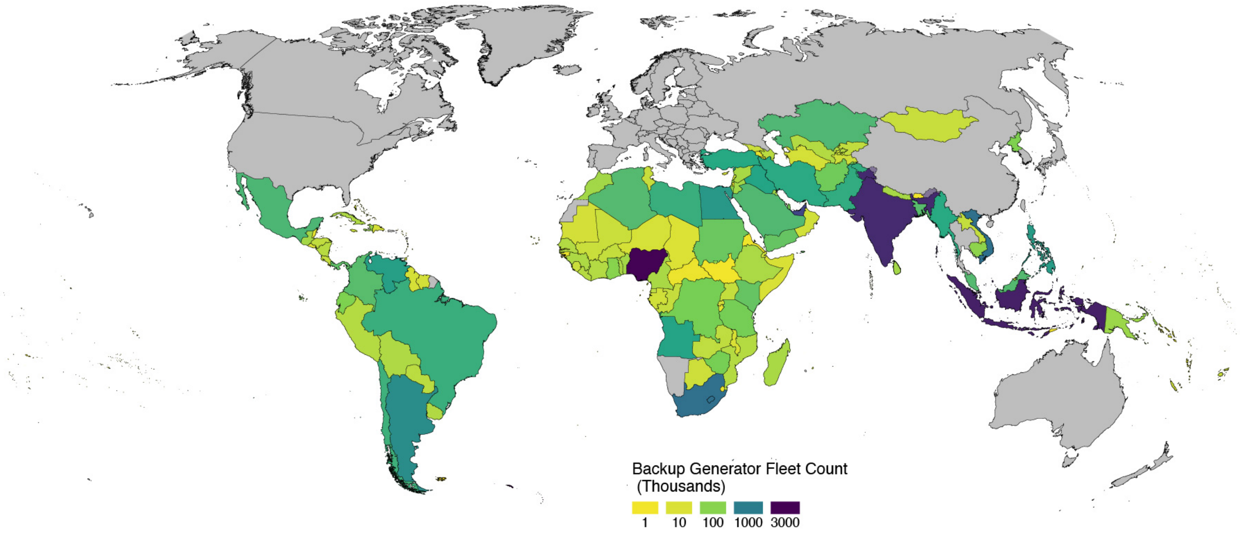
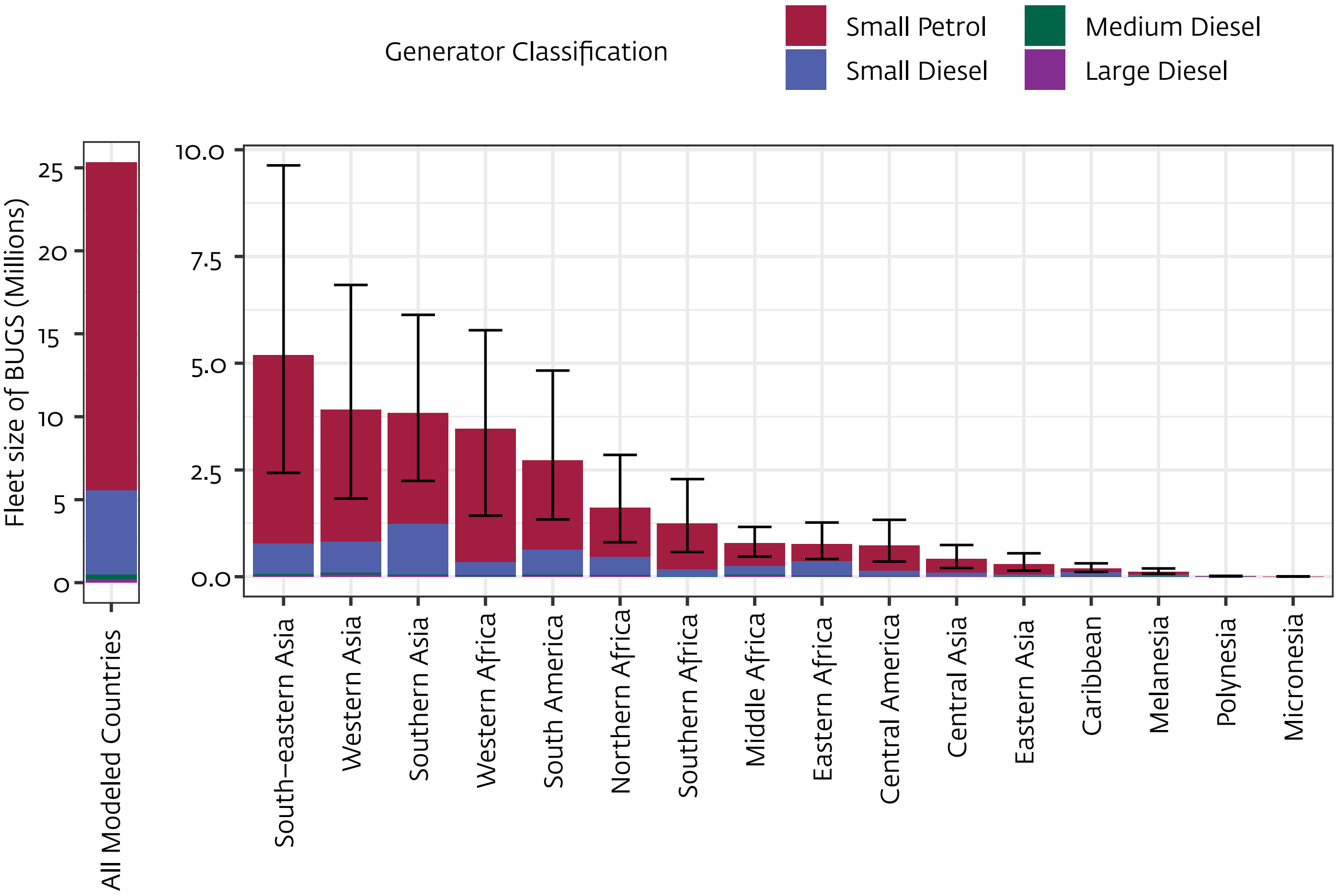


FIGURE 4.2: BACKUP GENERATOR SIZES BY REGION AND SIZE CLASSIFICATION



Error bars correspond to the 90 percent uncertainty interval

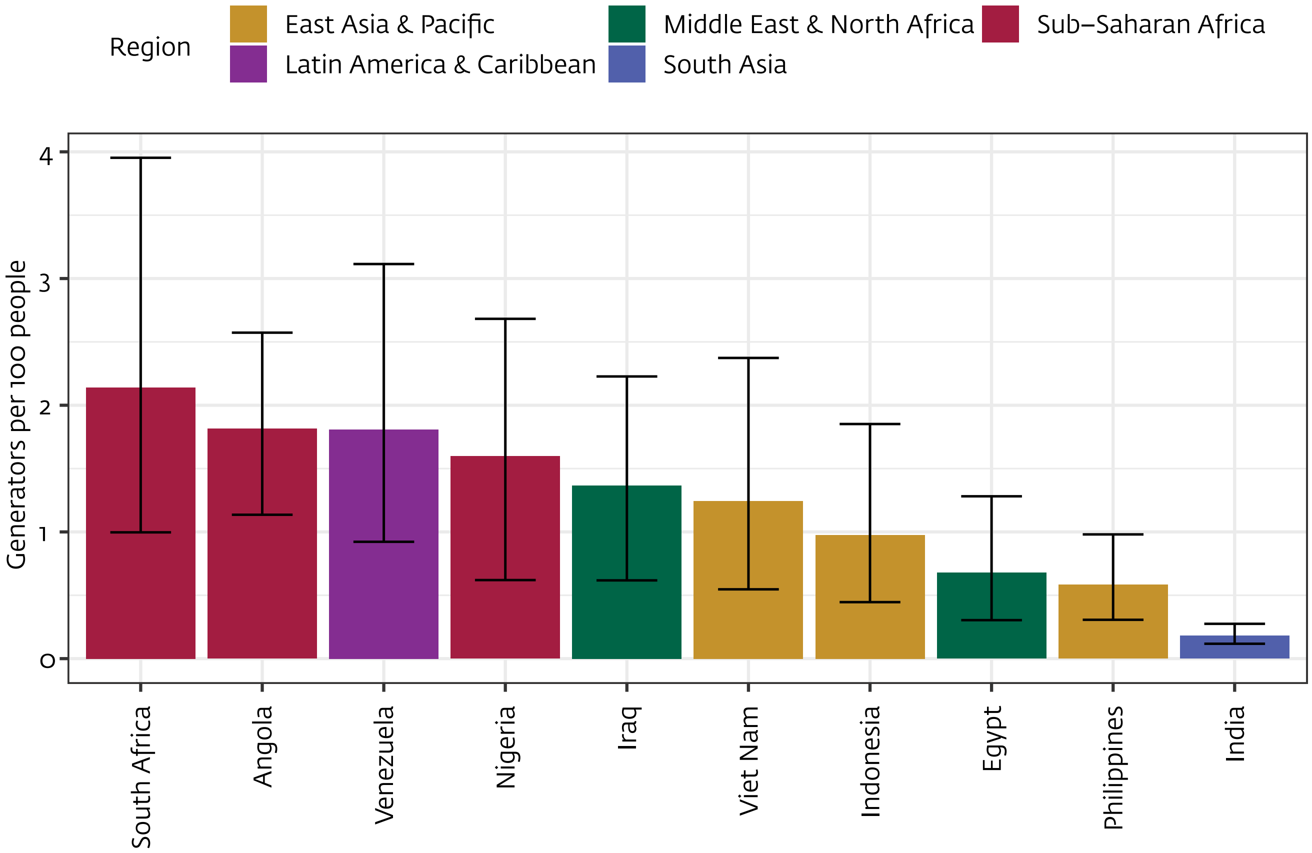
Figure 4.3 shows the number of generators per 100 people in the ten low- and middle-income countries (LMICs) with the largest total fleets. Within this group, there is one generator for every 165 people (30 households). In Nigeria, which has one of the largest fleets at three million deployed units, there is one generator for every 60 people (12 households). It is important to note that while fleet size is an important component for assessing the resulting impacts of generator operation, it does not necessarily reflect populations' reliance on them or their resulting impacts in that area.

Installed Fleet Capacity

We estimate that BUGS account for 450 GW (90 percent UI: 275 to 650 GW) of installed generating capacity across modeled countries (**Figures 4.4 and 4.5**). By comparison, the capacity of a typical coal-fired power plant is 0.5 GW (500 MW),[18] making the capacity of generator fleets currently deployed in developing countries equivalent to 900 (90 percent UI: 550-1300 GW) power plants. Considering only LMICs, the total fleet capacity is 350 GW (90 percent UI: 220 to 530 GW), a 22 percent reduction. This change is largely attributed to the exclusion of seven countries in the Middle East with particularly large fleets.

A small number of countries in Africa and Asia account for most of the installed capacity of backup generators. The twelve countries[19] with the largest fleet capacities account for 40 to 60 percent of all backup generating capacity across modeled countries; the top thirty-two (20 percent) modeled countries account between 60 and 90 percent of the total backup capacity. Based on central estimates, Sub-Saharan Africa accounts for roughly 20 percent of the population living in countries modeled, but 25 percent of total installed capacity—the largest fraction of any single region. East and South Asia combined (excluding China) account for 50 percent of the population living in countries modeled, but 36 percent of the total installed capacity. Among LMICs with the largest

FIGURE 4.3: PREVALENCE RATE OF BUGS IN THE TEN LOW- OR MIDDLE-INCOME COUNTRIES WITH THE LARGEST FLEETS, EXPRESSED AS GENERATOR UNITS PER 100 PEOPLE



Error bars correspond to the 90 percent uncertainty interval. Note that direct drive generators for agricultural and industrial applications are not included as part of generator fleet size estimates.

fleet capacities, India, Angola, Indonesia, Nigeria, and the Philippines account for 10 percent, 9 percent, 8 percent, 5 percent, and 4 percent of capacity across all modeled countries, respectively.

Accounting for installed capacity of generators on the power grid indicates that BUGS make up a significant fraction of electricity generating capacity in developing countries. Across all modeled countries, backup generator capacity is equivalent to 27 percent (90 percent UI: 18 percent, 40 percent) of the capacity of power plants on the grid, and accounts for 22 percent (90 percent UI: 15 percent, 29 percent) of total generating capacity—grid and backup capacities combined.[20] In Sub-Saharan Africa, the backup capacity is roughly equal to that of power plants on the grid; excluding South Africa, installed backup capacity is twice that of the grid.

Energy Generation

BUGS provide 130 terawatt hours (TWh) (90 percent UI: 68 to 260 TWh) of energy service per annum across modeled countries (**Figures 4.6 and 4.7**). By comparison, a typical coal-fired power plant generates 3 TWh[21] in a typical year, making the service provided by BUGS equivalent to that of 43 (90 percent UI: 23 to 87) power plants. These energy services are distributed across a range of countries and regions, not just in areas with the poorest grid reliability or largest populations and generator fleets. Considering only LMICs, annual generation is 120 TWh (90 percent UI: 63 to 234 TWh). This modest 8 percent change to total generation relative to the larger 22 percent change observed for installed capacity is indicative of the low utilization rates (reliable grids) of several high-income countries with substantial backup fleets, primarily in the Middle East.

FIGURE 4.4: INSTALLED CAPACITY OF BUGS ACROSS ALL MODELED COUNTRIES

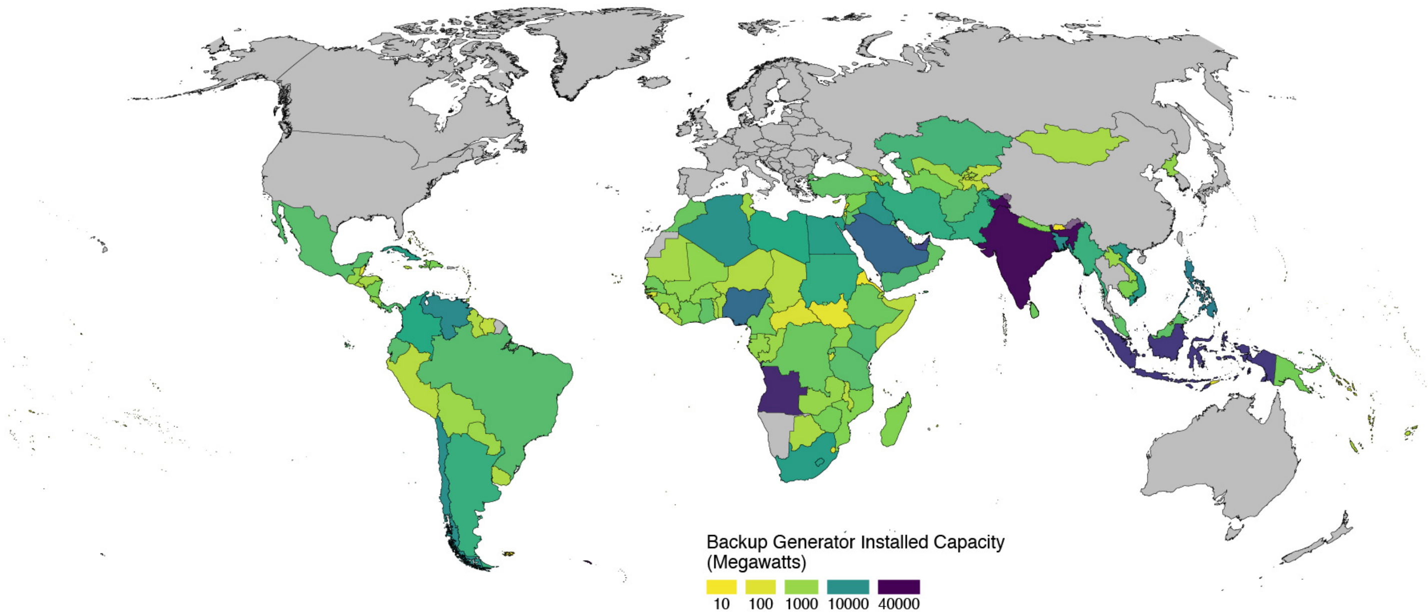
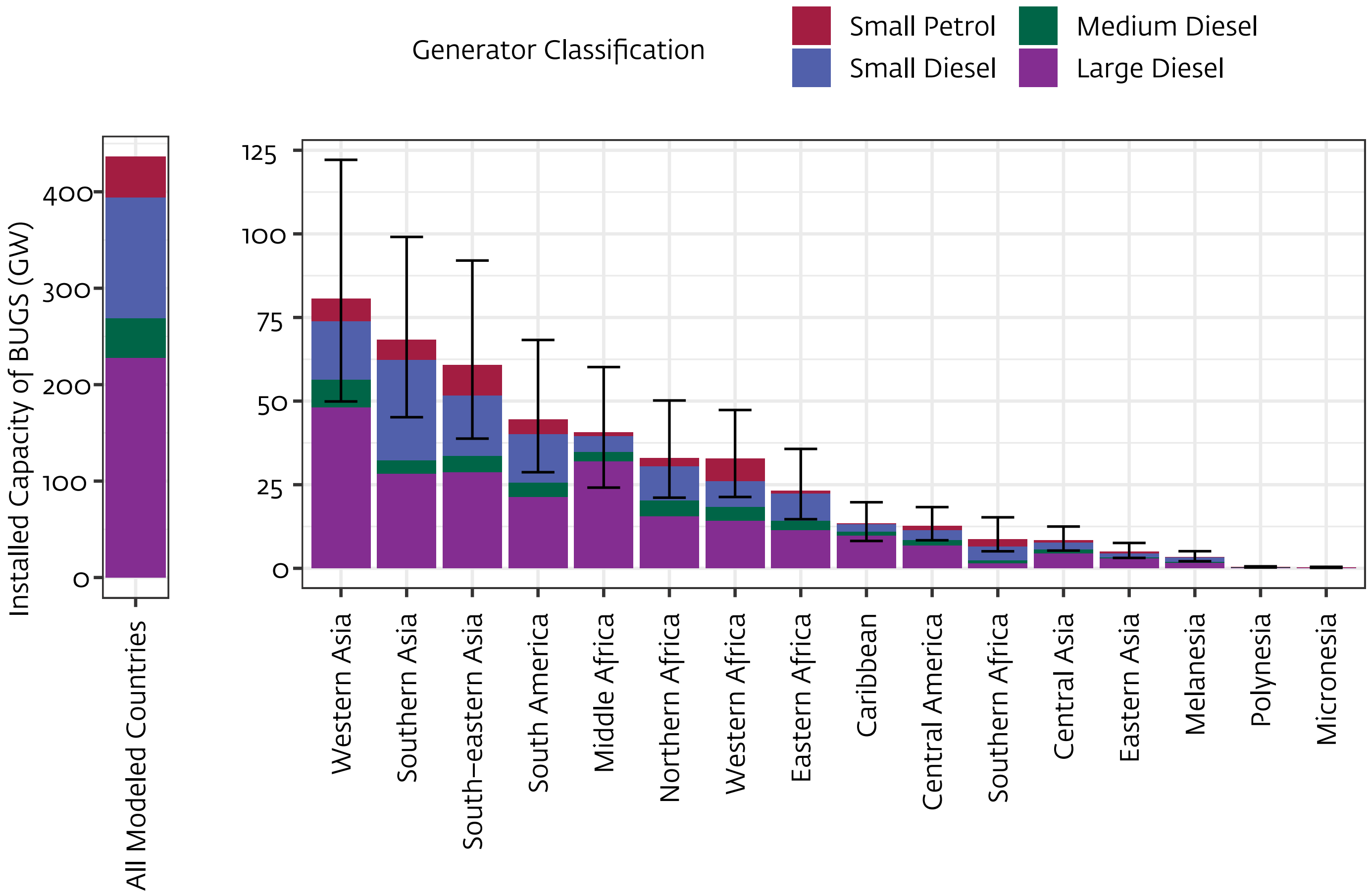


FIGURE 4.5: INSTALLED CAPACITY OF BUGS ACROSS ALL MODELED COUNTRIES BY REGION AND GENERATOR SIZE CLASSIFICATION



Error bars correspond to a 90 percent uncertainty interval.

FIGURE 4.6: ENERGY GENERATION BY BUGS ACROSS ALL MODELED COUNTRIES

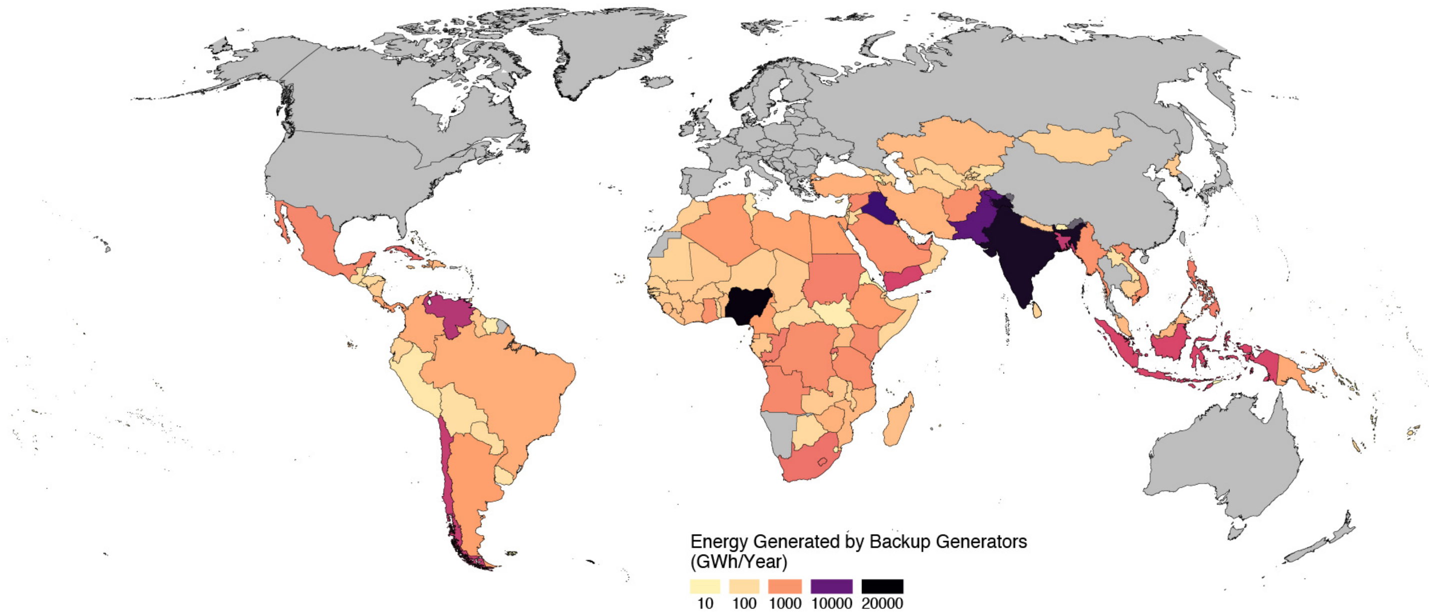
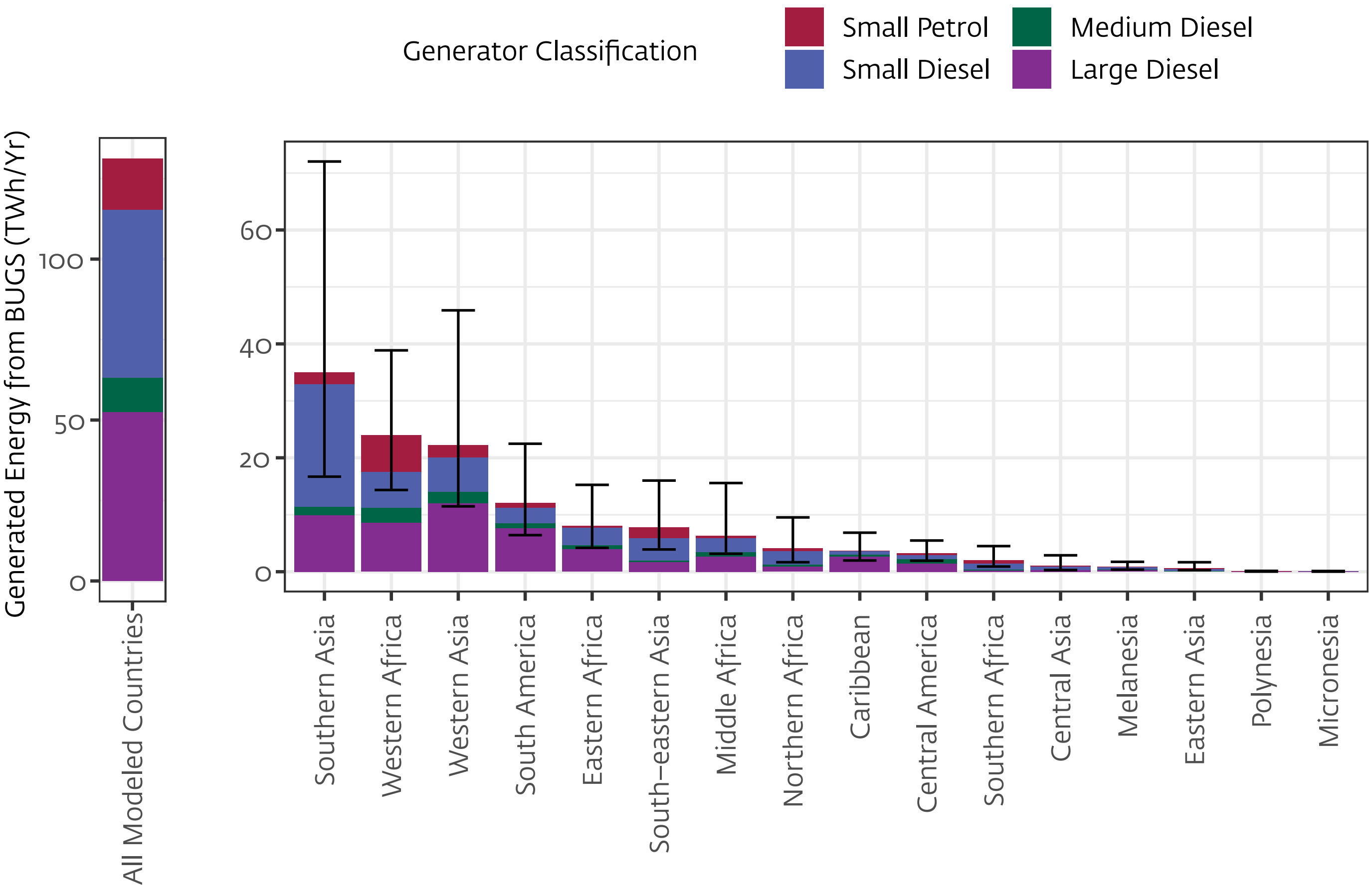
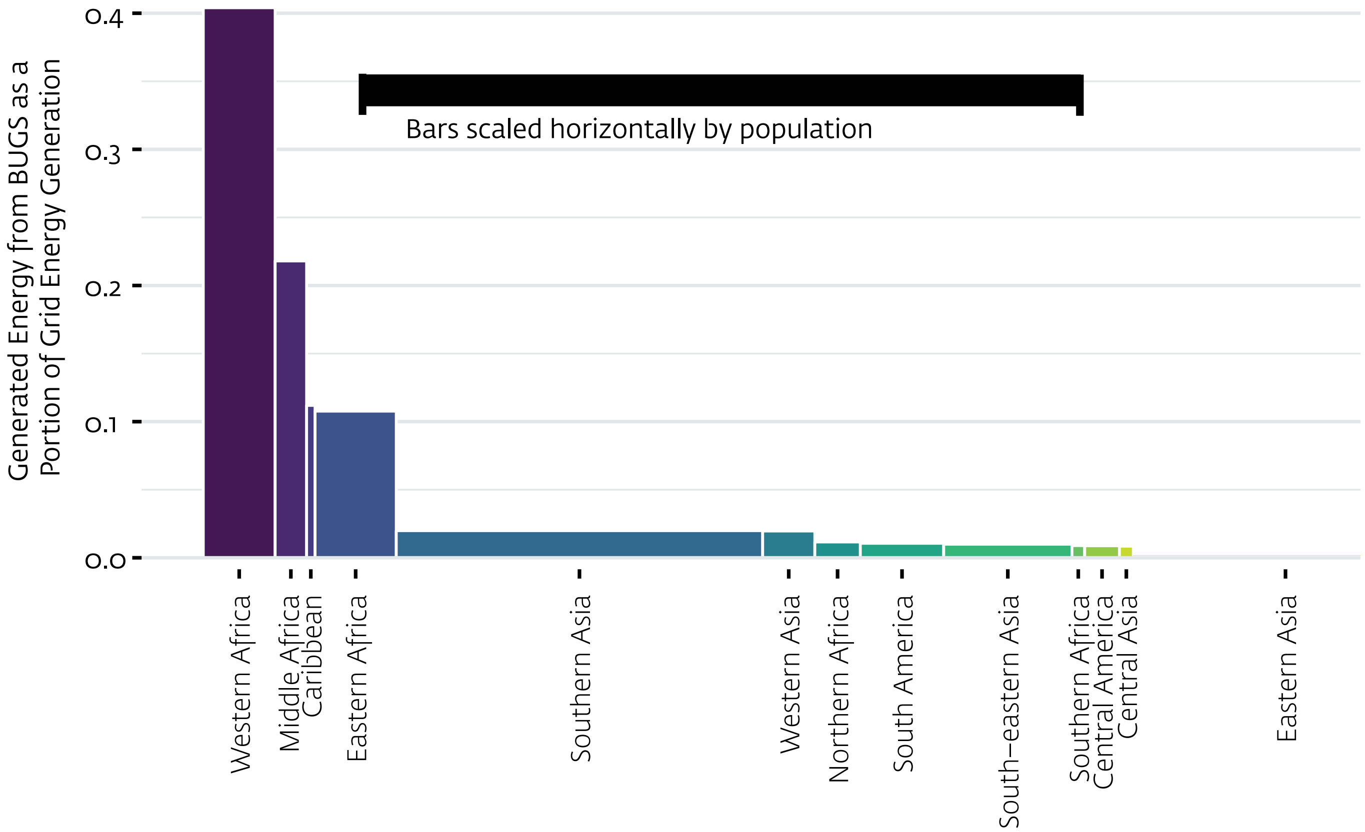


FIGURE 4.7: ENERGY GENERATION FROM BUGS ACROSS ALL MODELED COUNTRIES BY REGION AND GENERATOR SIZE CLASSIFICATION



Error bars correspond to a 90 percent uncertainty interval

FIGURE 4.8: GENERATION FROM BUGS AS A PORTION OF GRID GENERATION (RATIO) BY REGION



The horizontal width of bars is scaled based on regional populations.

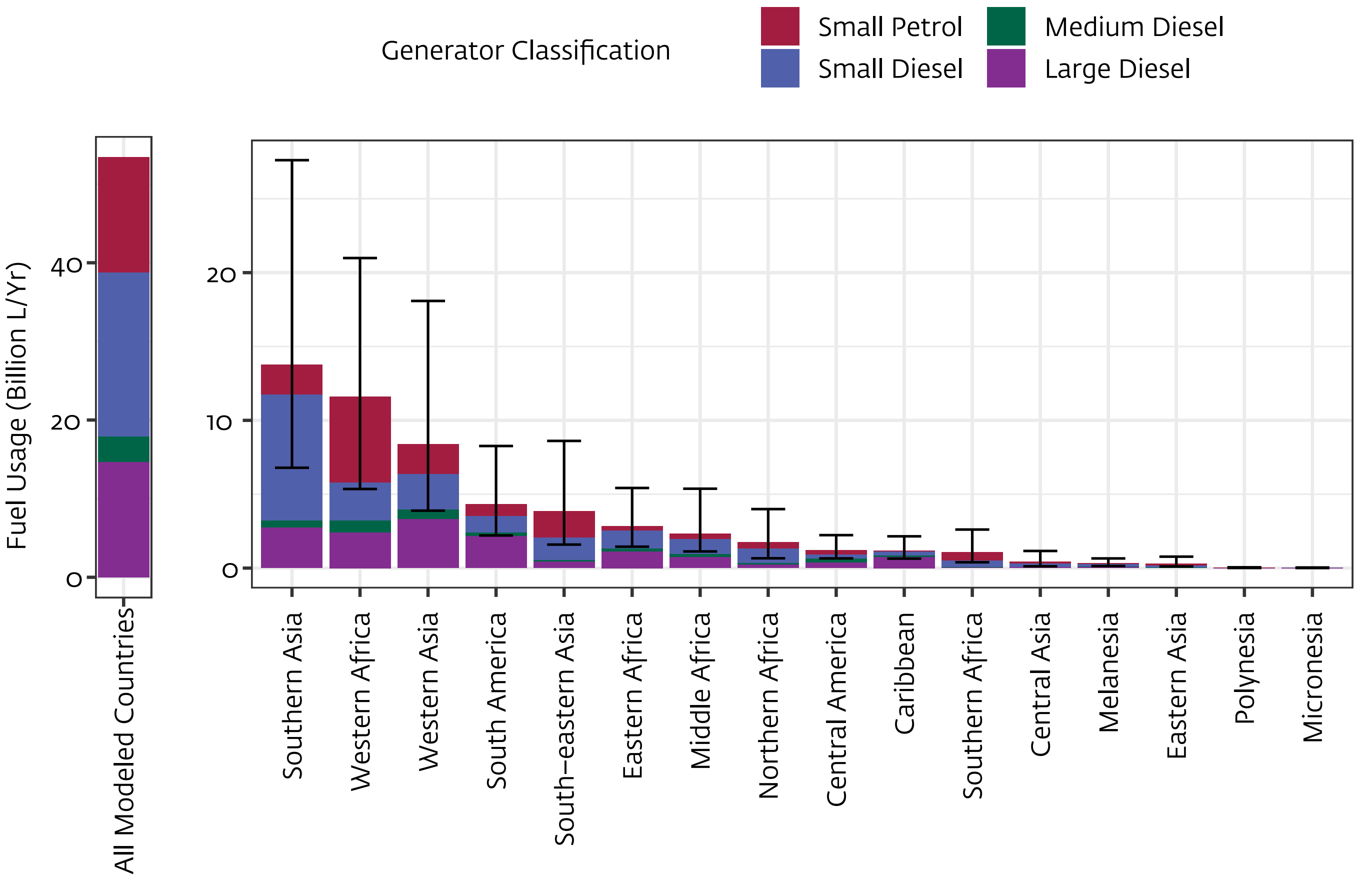
Energy services (generated energy) from backup generation are heavily concentrated within several countries in Africa and to a lesser extent Asia. The five countries with the most generation account for 50 to 60 percent of all backup generator service; fifteen (9 percent) of the 167 modeled countries account for 70 to 80 percent of the total service provided by BUGS. Using central estimates, Sub-Saharan Africa alone accounts for 30 percent of total backup generation, the most of any single region, but roughly 20 percent of the population living in countries modeled. East and South Asia, excluding China, together account for roughly the same fraction of total backup generation as Sub-Saharan Africa, but 50 percent of the population living in countries modeled. Among the LMICs, Nigeria, India, Iraq, Pakistan, and Venezuela account for 16 percent, 15 percent, 11 percent, 9 percent, and 4 percent of all backup energy service from generators.

A comparison of the amount of generated energy provided from BUGS to service from the grid provides a better sense of the degree to which various populations are dependent on backup sources of electricity (**Figure 4.8**). The impact of poor grid reliability is particularly pronounced across Sub-Saharan Africa, where the energy service provided from BUGS is equal to 11 percent (90 percent UI: 6 to 21 percent) of that from the grid.[22] Western Africa is among the most affected, where the energy generated each year from backup generator sets is equivalent to 40 percent that of the grid.

Fuel Consumption

55 billion liters (90 percent UI: 25 to 110 liters) of diesel and gasoline are consumed annually by BUGS (**Figure 4.9**). Diesel accounts for the majority of total consumption, at 38 billion liters per year (70 percent). Gasoline consumption is slightly less than half that of diesel at 17 billion liters per year (30 percent). Although gasoline generating units outnumber diesel units in the fleet by approximately three to one, the maximum capacity of a

FIGURE 4.9: ANNUAL GASOLINE AND DIESEL FUEL USED IN BUGS BY REGION AND GENERATOR SIZE CATEGORY



Error bars correspond to a 90 percent uncertainty interval.

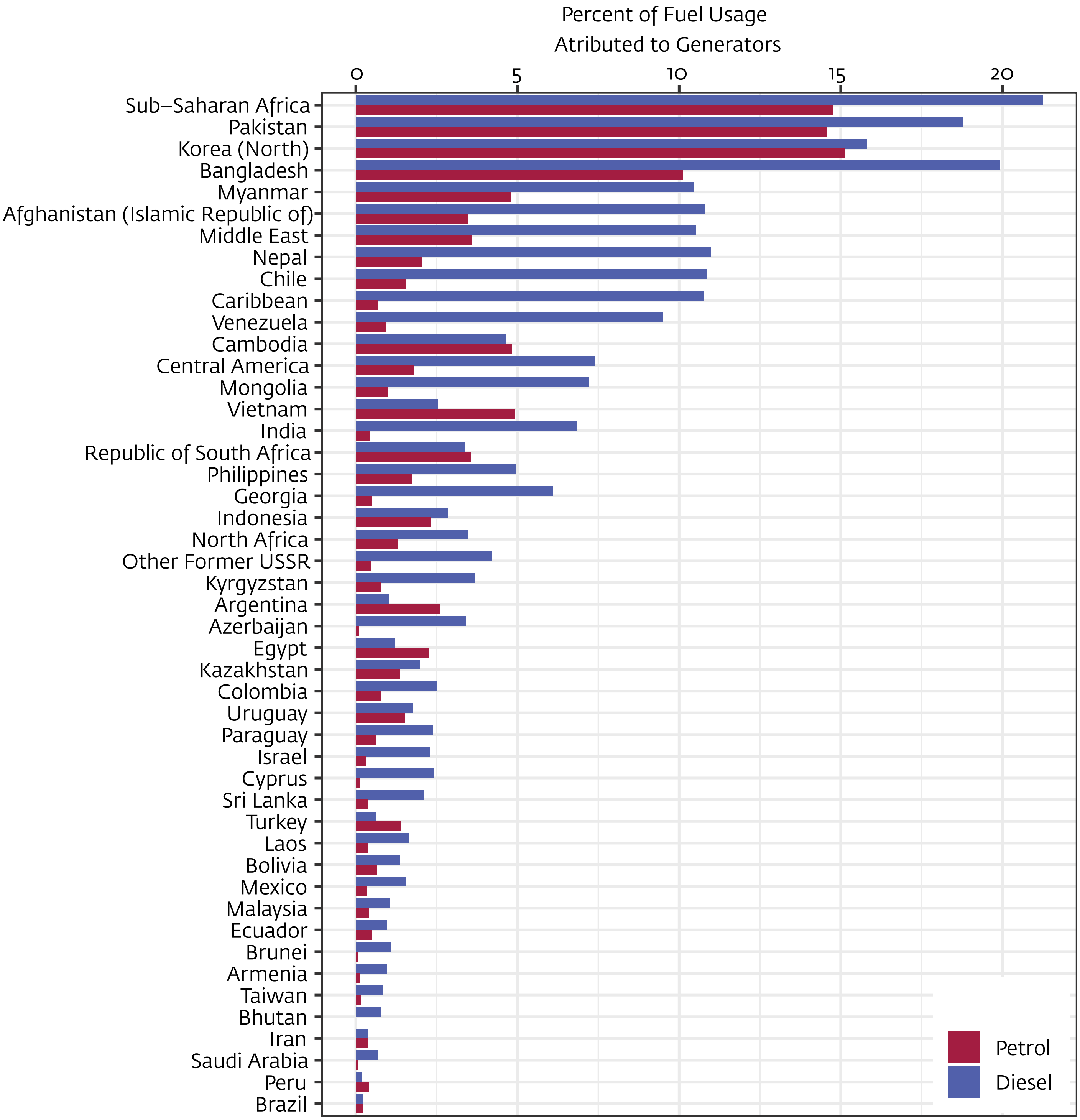
gasoline generator is considerably lower than the average diesel generator, reducing fuel requirements. The distribution of fuel consumption across regions closely mirrors that of generation, with Southern Asia and Western Africa accounting for the greatest portions, at 26 percent (14 billion liters) and 22 percent (12 billion liters), respectively.

Small sized diesel and gasoline BUGS account for roughly two thirds of all diesel or gasoline fuel (35 billion liters) consumed for backup generation across modeled countries. In Western Africa, where the fleet and operation time of gasoline generators is especially high, gasoline accounts for half of all fossil fuel consumed for backup electricity generation—nearly five times the fraction of other regions in Sub-Saharan Africa (excluding Southern Africa) and more than three times that of South Asia.

Powering BUGS accounts for a significant portion of total fossil fuel demand in several regions and countries (**Figure 4.10**). In Sub-Saharan Africa, generators account for nearly 15 percent of total gasoline consumption and 22 percent of total diesel consumption. Several countries in South Asia also have meaningful fractions of diesel and gasoline fuel being used in generators, including Pakistan (20 percent), Bangladesh (22 percent), Nepal (9 percent), and India (4 percent).

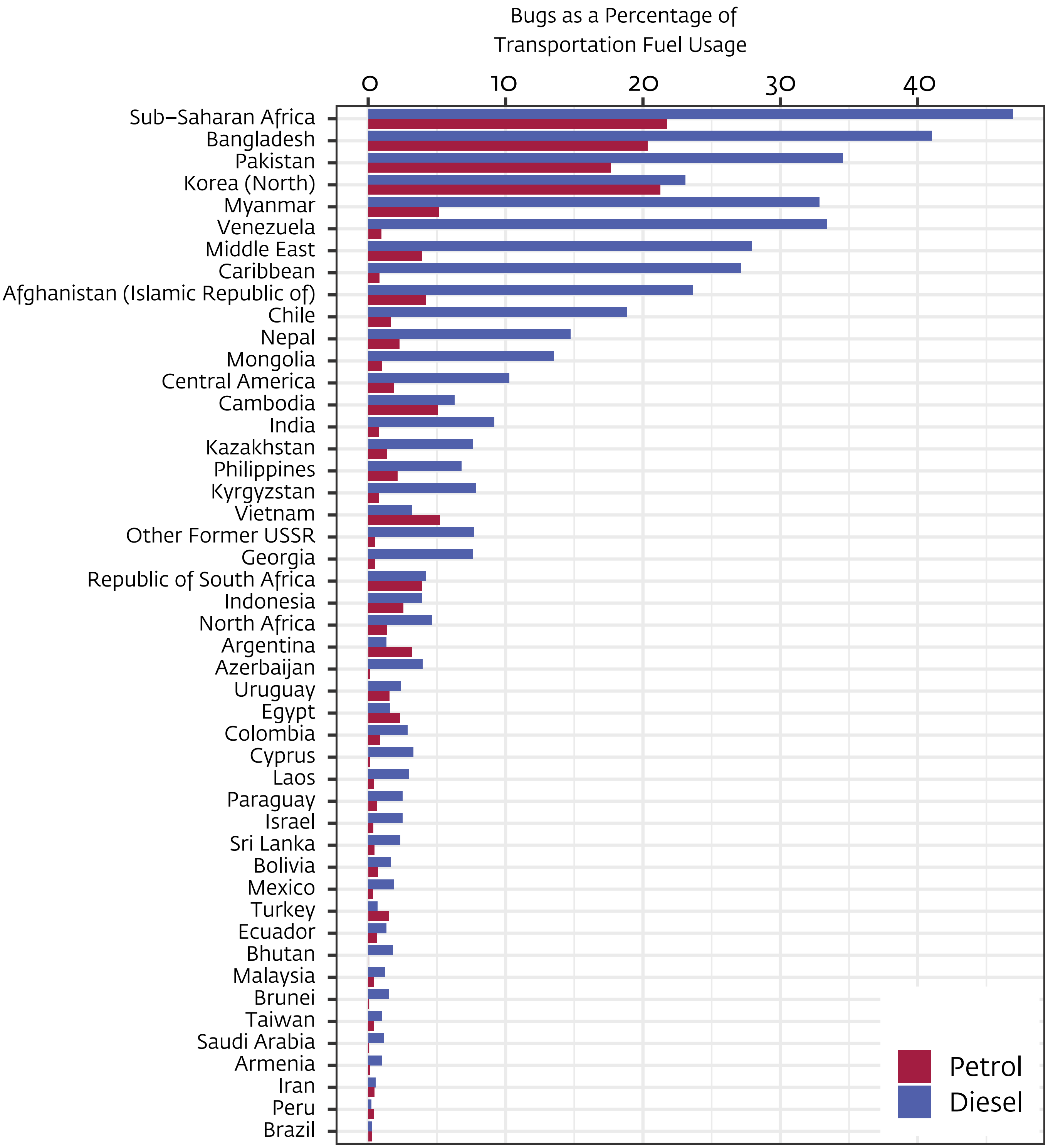
Figure 4.11 shows generator fuel consumption as a percentage of transportation sector demand, the single largest consuming sector in all countries and regions. In the absence of detailed accounting of fossil fuel use, as is the case in many LMICs, it is often assumed that nearly all fossil fuel is used for transportation. Our results reveal, however, that in areas with weak and failing grids, demand for BUGS are comparable to that of leading *sectors* with respect to fossil fuel demand. In many locations, including Sub-Saharan Africa and several countries in South Asia, the quantity of fuel required for generators is upwards of 20 percent of the amount of diesel used for transportation, and upwards of 10 percent of the amount of gasoline.

FIGURE 4.10: DIESEL AND GASOLINE CONSUMPTION FOR POWERING BUGS AS A PERCENTAGE OF TOTAL FUEL CONSUMPTION



Fuel estimates were compared to IEA statistics so that the overall energy use is consistent with IEA. Regional and country classifications are based on those used in the GAINS model.

FIGURE 4.11: BUGS FUEL CONSUMPTION AS A PERCENTAGE OF FUEL CONSUMED IN THE TRANSPORTATION SECTOR



Fuel estimates were compared to IEA statistics so that the overall energy use is consistent with IEA. Regional and country classifications are based on those used in the GAINS model.

THE ECONOMIC COSTS OF BACKUP GENERATORS

Capital investment

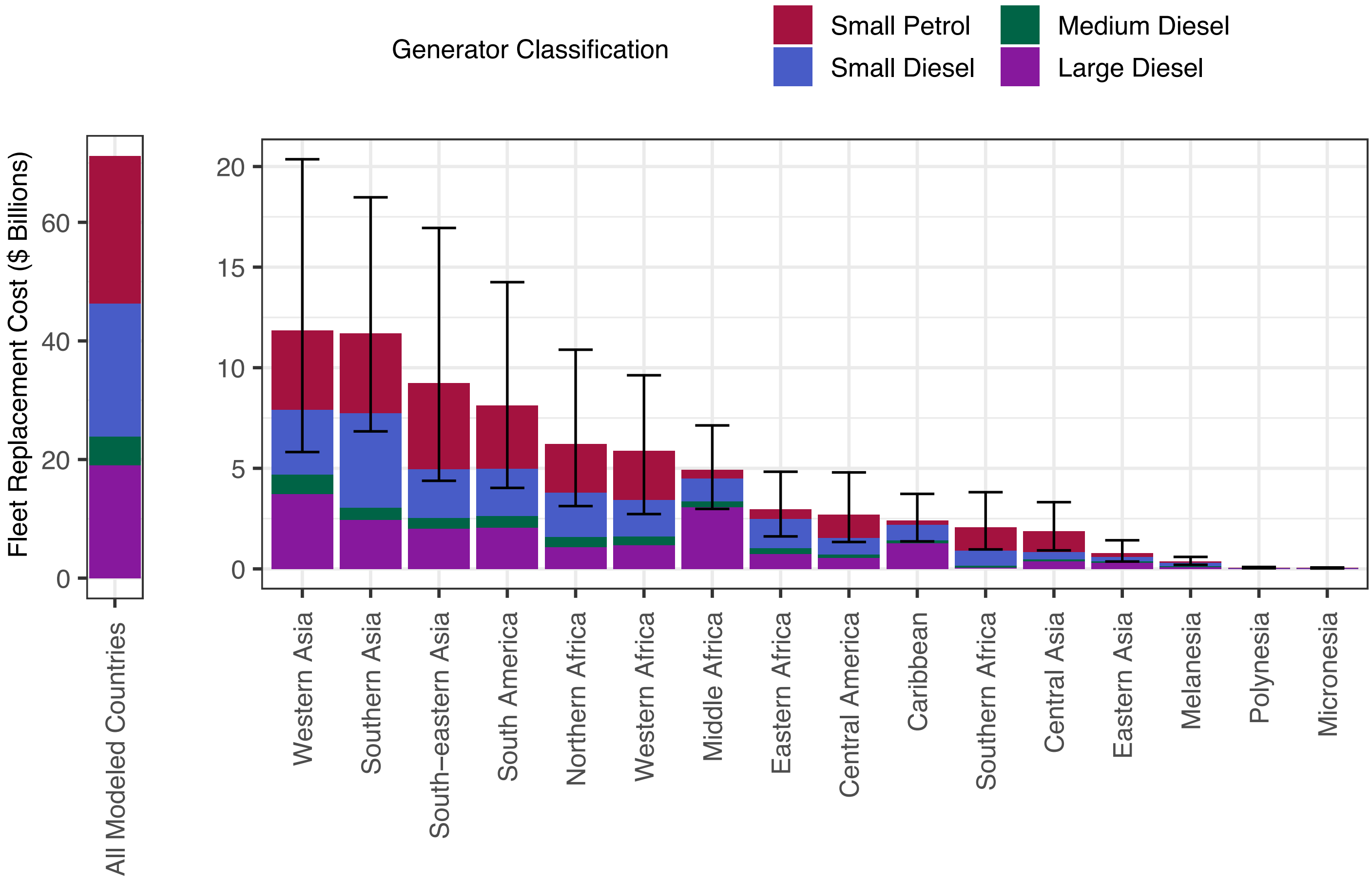
Over 1.2 million generators were transferred to developing countries through international trade in 2016, with a total value of $5.3 billion. From 2011 to 2016, import values totaled $45 billion, averaging $9 billion per year over this time period.[23] Diesel generating units accounted for only 25 percent of total units sold, but 80 percent of total import value in 2016. We estimate the replacement value of the generator fleet across all modeled countries to be approximately $70 billion.[24] These estimates are before accounting for local taxes, duties, and distribution costs.

Figure 4.12 shows the estimated value of backup generator fleets across modeled regions, assuming average 2016 unit costs. Small gasoline ($25 billion) and small diesel ($22 billion) dominate globally and across all regions with the largest fleets. Large diesel units are not far behind, with a replacement cost of $19 billion. Medium sized diesel units comprise the smallest fraction, at $4.9 billion. It is important to note that although small gasoline and small diesel are valued similarly, small gasoline generators are typically less robust and require replacement more frequently than diesel units.

Fuel Related Costs

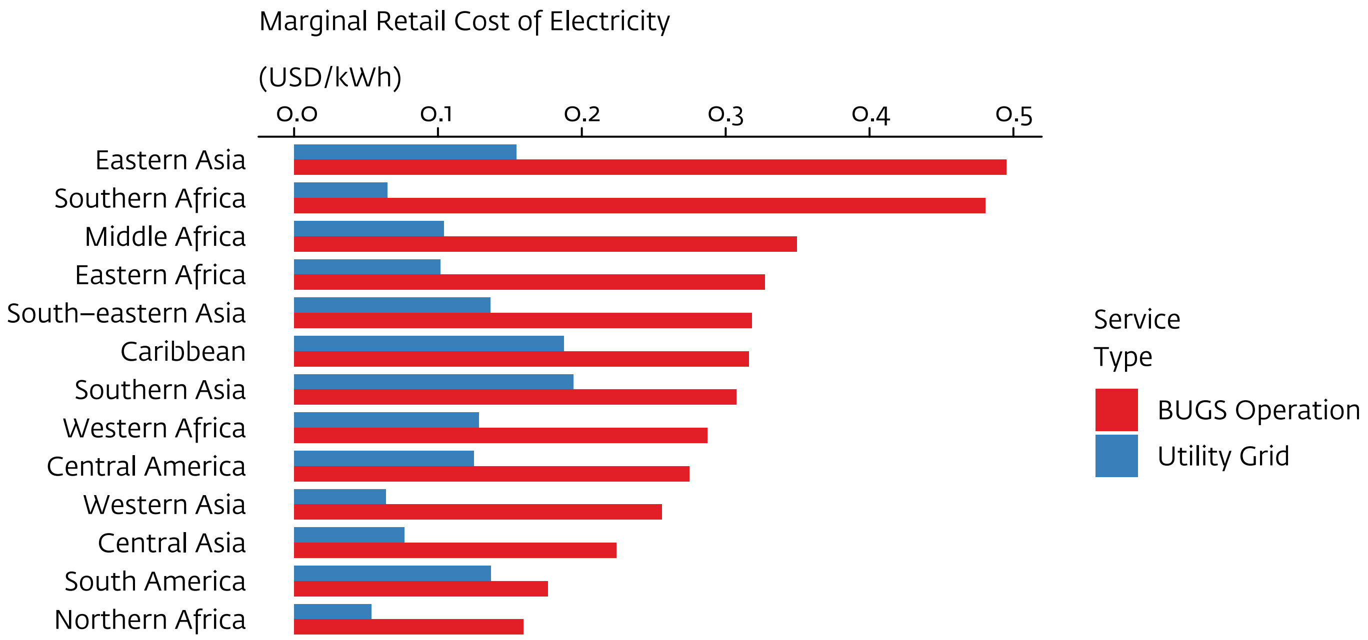
Expenditures on fuel for BUGS is estimated at $40 billion per year, or eight times the annual investment in the generators themselves in 2016. **Figure 4.13** shows how there is a vast range in the marginal fuel cost of backup generator operation, from $0.20 to $0.50 per kWh. These differences are mainly due to differences in the retail cost of gasoline and diesel, but also include variations in the makeup of generator fleets (e.g., generator types, capacity) and assumptions about the part-load efficiency and capacity factors of generators during operation. It is important to note that marginal costs reported here are for the cost of the fuel alone, and do not consider capital or

FIGURE 4.12: REPLACEMENT COST OF BACKUP GENERATOR FLEETS



Error bars correspond to the 90 percent uncertainty interval of totals.

FIGURE 4.13: ESTIMATED SERVICE COSTS FOR BUGS BASED ON FUEL PRICES ALONE, WITH COMPARISONS TO THE AVERAGE COST OF ELECTRICITY FROM UTILITY GRIDS



The midpoint estimate of backup generator marginal cost is shown.

maintenance costs, or the external costs of pollutant emissions and other impacts on welfare.

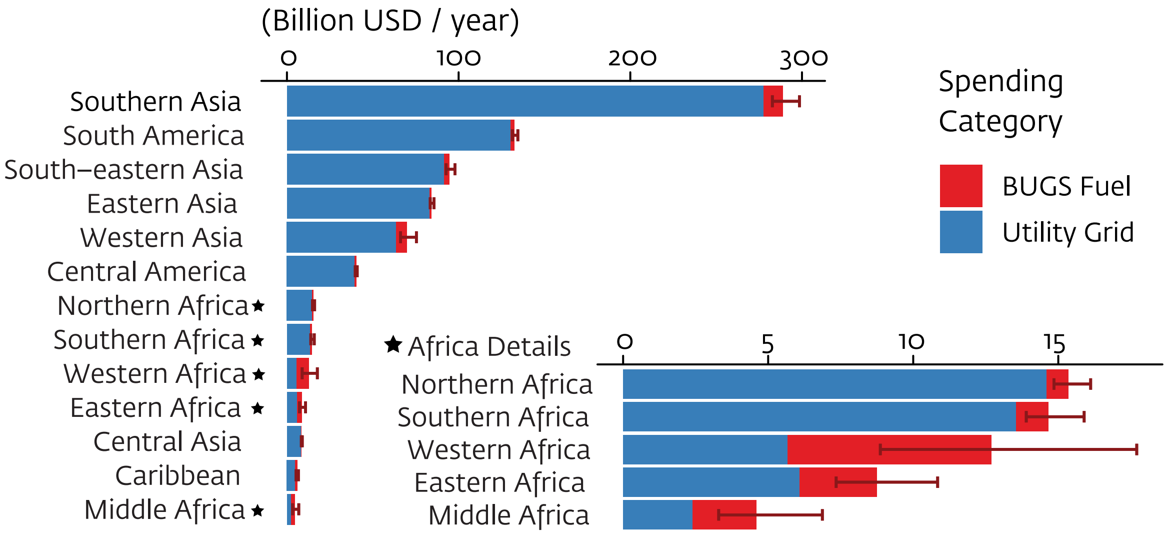
In every region the grid is lower cost than BUGS. These marginal costs of service provide a benchmark against which solar + storage and other strategies could compete. During blackouts, service from solar + storage, for example, would avoid the marginal fuel cost of backup generator use. During normal operation, the generation from onsite solar could also offset retail electricity consumption.

Another view on the cost of fuel for BUGS versus grid service is to compare overall spending on each category of service, showing the overall scale of each electricity access pathway. **Figure 4.14** shows how these two energy sources compare across regions. In much of Asia and the Americas, there are large and heavily relied upon utility grids that provide the vast majority of energy service. Thus, spending on grid-based power is dominant in these regions, albeit with significant spending on BUGS as well, between $1 billion and $10 billion per year. In Africa, however, the scale of spending on BUGS is similar to the grid. Western Africa spends approximately the same amount on generator fuels as it does for grid electricity, and in specific countries (such as Nigeria) there is more spending on generator fuel than on the grid. The implication is that deployment of strategies that support electricity service in Africa are just as much or more a story of reducing the reliance on BUGS with distributed systems as it is one of providing clean energy through grid-serving renewables.

Consumption Subsidies

We estimate that the cost of subsidizing fuel used in BUGS was $1.6 billion (90 percent UI: $0.8 to $3.2 billion) in 2016. Like the fleet characteristics discussed in previous sections, much of the subsidy cost is concentrated in a few countries with large unit subsidies. While modest in comparison to other costs of backup generation, it is important to consider that the consumption subsidies reported here are before adding production subsidies and external costs of pollutant emissions on health and climate, which can be considerable. A recent valuation of global fossil fuel subsidies conducted by the International Monetary Fund (IMF) found pollutant impacts on climate and air quality to account for over half of the total cost.[25] Given the highly concentrated nature of generator fleet deployments, it is reasonable that external costs would have a similarly large contribution if valued. In effect, the true cost of fossil fuel use for BUGS could be roughly twice the $40 billion mentioned above, if we account for the pollutant impacts discussed in the next section.

FIGURE 4.14: TOTAL SPENDING BY RETAIL CUSTOMERS ON FUEL FOR BUGS AND UTILITY GRID SERVICE



The total spending on utility grid service is shown for comparison to BUGS. The spending on fuel for generators includes a 90 percent uncertainty interval error bar.

POLLUTANT EMISSIONS

Like the emissions from the engines of cars and motorcycles, the "tailpipe" emissions of BUGS contain thousands of chemicals, including many that impact human health and the environment. A key objective of this study was to establish the most comprehensive coverage to date on the current (baseline) emissions from BUGS in developing countries based upon the characteristics of their fleets and the energy service they provide.

Our results reveal that BUGS are a significant source of pollutant emissions in many countries and regions. Measuring generator performance and impacts in areas with frequently operated fleets could reveal they are an even more significant local source of air pollution, and mitigation opportunity, than indicated here. One implication of our work is an increased recognition of BUGS as a source of pollutant emissions in most developing countries and regions of the world.

High Priority Opportunity for Pollution Reduction

Air pollution is a leading cause of premature death and disease in many countries. This is especially true in developing countries, where exposure to particulate matter (PM) air pollution was responsible for 2.5 million premature deaths in 2016, with an additional 400 thousand premature deaths resulting from exposure to ground-level ozone.[26] Many of the same pollutants that harm health also contribute to climate change and can have adverse effects on ecosystems. A critical step toward mitigating these pollutant impacts is identifying and controlling important pollutant sources. Despite the pervasive use of BUGS across developing countries, a limited understanding of their contribution to local and regional pollutant emissions persists and hampers the ability to assess the benefits of strategies that reduce their operations. As a source of pollution that has been poorly understood to date, the global and local burdens resulting from generator emissions represent unaccounted costs of operation, and eliminating them provides extended value from programs that mitigate generator use, beyond monetary savings from avoided fuel and other expenses.

Existing evidence suggests that BUGS can be a potentially important source of local and regional air pollution in developing countries. Compared to power plants on the grid, BUGS can emit several times more pollution from each unit of fuel burned and unit of electricity delivered.[27] When deployed at scale, as they often are in weak-grid areas, BUGS have been found to be an important source of local and regional air pollutants. A recent assessment of sources of pollution in 20 cities across India indicate that BUGS account for 2 to 6 percent of total ambient $PM_{2.5}$,[28] while a separate study of Indian cities found BUGS to account for between 8 and 28 percent of $PM_{2.5}$ in the residential areas they examined.[29] Several studies examining various parts of the African continent have reported that BUGS are a significant and growing source of NO_x emissions, and an important contributor to ozone-forming pollutants.[30] An accounting of BUGS emissions based on existing country and regional estimates of fuel consumption found BUGS to be a modest contributor to pollutant emissions globally, but a potentially important source of local black carbon (BC) and NO_x emissions, especially in developing countries.[31] Two previous reports from the World Bank found BUGS to be a modest contributor to black carbon (BC) emissions in Nigeria and the Kathmandu Valley of Nepal, but noted that limited data were available on the size and characteristics of generators in the fleet. Nearly all existing studies on BUGS impacts have focused on diesel generators only, and estimated generator operations by assuming power plants on the grid represent total electricity demand, or do not explicitly connect the energy services of BUGS to their emission impacts.

Several of the pollutants in generator emissions are of particular importance given the robust evidence of their effects on health and the environment. The emissions from BUGS contribute, either directly or indirectly, to all pollutants found on major priority pollutant lists. The World Health Organization (WHO) recognizes four pollutants relevant to outdoor air pollution: particulate matter, ozone (O_3), nitrogen dioxide (NO_2), and sulfur dioxide (SO_2), all of which are directly emitted or formed from pollutants found in generator exhaust fumes. **Table 4.1**[32] provides a brief summary of several important pollutants associated with backup generator operation.

The emissions from BUGS contribute, either directly or indirectly, to all pollutants found on major priority pollutant lists.

TABLE 4.1: A SUMMARY OF HEALTH AND CLIMATE RELEVANT POLLUTANTS ASSOCIATED WITH THE EMISSIONS OF BACKUP DIESEL AND GASOLINE GENERATORS

Pollutant	Major Impact Areas	Estimated in This Study	Description
Carbon Dioxide [CO_2]	Environment	Yes	CO_2 is the single most important contributor to climate change.
Particulate Matter, Black Carbon, Organic Carbon [$PM_{2.5}$, BC, OC]	Health, Environment	Yes	$PM_{2.5}$ is perhaps the best pollutant indicator for health risk; combustion of fossil fuels, like diesel, is a major source globally, especially in urban populations. Once in the atmosphere, $PM_{2.5}$ goes on to affect air quality, while black (BC) and organic carbon (OC), components of $PM_{2.5}$, contribute to climate impacts. The importance of BUGS as a source of $PM_{2.5}$ health risk is dependent on other sources of $PM_{2.5}$ nearby. In cities, for example, vehicle emissions are a dominant source. Black carbon (BC) and organic carbon (OC), components of particulate matter, in addition to health risks, absorb and reflect solar radiation leading to climate impacts.
Nitrogen Oxides [NO_x]	Health, Environment	Yes	Most NO_x emissions come from the combustion of fossil fuels and are typically associated with the vehicle and energy generation sources. Once emitted, NO_x form pollutants that damage health (i.e., ozone, particles) and the ecosystem (i.e., acid rain, ozone). Exposure to NO_x has been associated with numerous respiratory illnesses. High levels of nitrogen dioxide are also harmful to vegetation—damaging foliage, decreasing growth and reducing crop yields. NO_x are ozone precursors, reacting with other pollutants in the air to form potentially harmful ground level ozone.
Sulfur Dioxide [SO_2]	Health, Environment	Yes	SO_2 is a pollutant emitted from burning fuels that contain sulfur, such as coal, diesel, and kerosene. Inhaling SO_2 can exacerbate respiratory diseases and can also form small particles, which contribute to PM exposure. In the atmosphere, SO_2 can contribute to acid rain and reduce visibility.
Carbon Monoxide [CO]	Health	No	CO is the leading cause of accidental poisonings globally. Carbon monoxide poisoning is a significant threat when generators are used inside or too close to occupied buildings.[33] This is especially true for smaller two-stroke generators often used by homes and small businesses.[34,35] CO is an ozone precursor, reacting with other pollutants in the air to form potentially harmful ground level ozone. This occurs close to the site of emission. It does not have any significant environmental effects at a global level.
Non-Methane Volatile Organic Compounds [NMVOC]	Health, Environment	No	NMVOCs are a large group of chemical compounds that easily evaporate into the surrounding air. Exposure to some NMVOCs such as benzene, formaldehyde, and acetone can pose direct health risks. NMVOCs are also ozone precursors, reacting with other pollutants in the air to form potentially harmful ground level ozone. The emissions of NMVOCs from generators are not reported here or well documented, but remain important, especially in areas with large numbers of gasoline-fueled generators.
Ozone [O_3]	Health, Environment	No	Formation of ozone in the lower atmosphere (ground-level ozone) occurs from reactions between NO_x (a component of NO_x), carbon monoxide (CO), and volatile organic compounds (VOCs) in the presence of ultraviolet light (UV). Unlike the ozone in the upper atmosphere, which protects from harmful UV radiation, ozone exposure in the air we breathe can lead to increased risk of various respiratory diseases, such as asthma, and cause abnormal lung development in children. We do not model the contribution of BUGS to ozone formation, but it has been identified as a potentially important source in Africa and particularly Nigeria.[36]

BUGS as Significant Source of Pollution

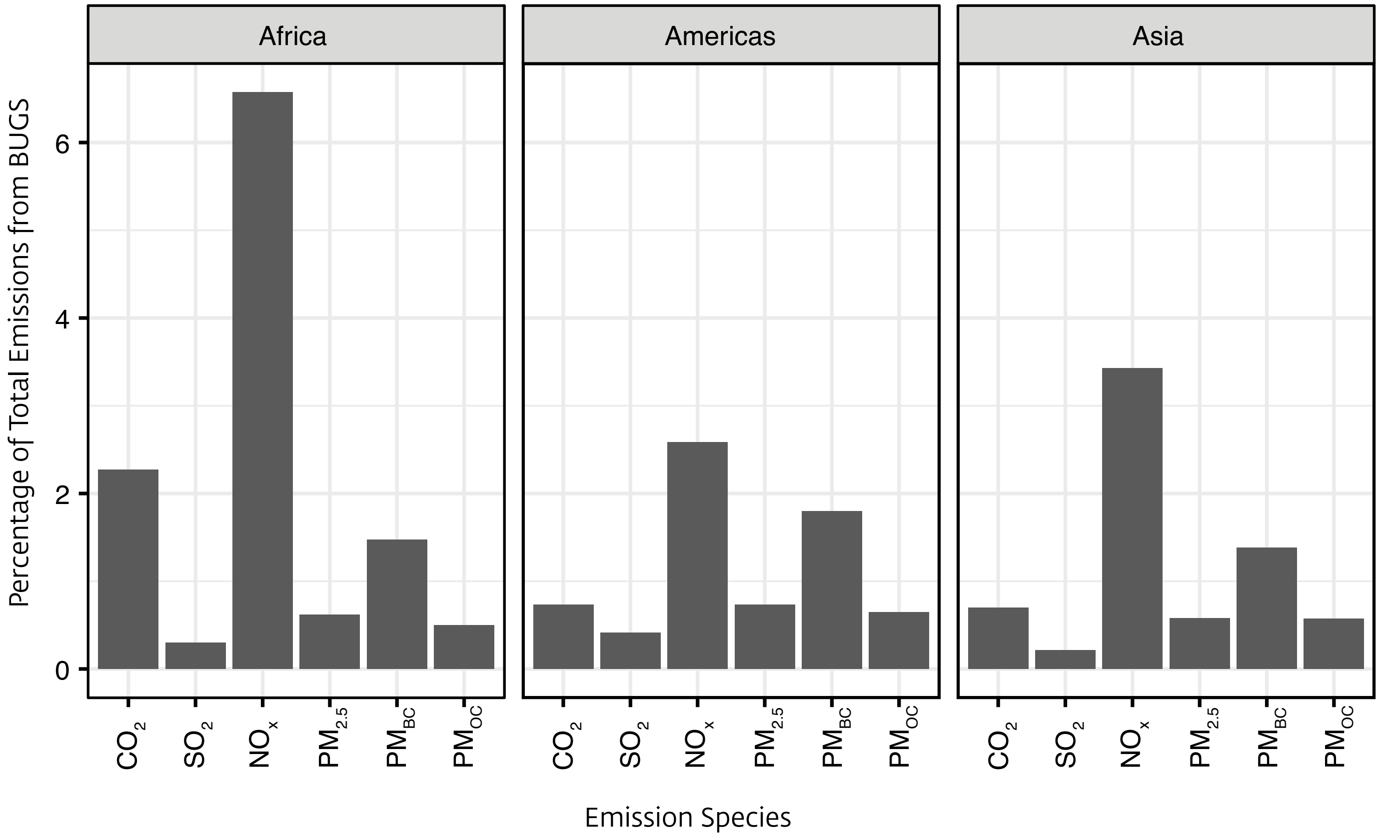
Backup generator fleets contribute significantly to some pollutant emissions, but their importance for reducing impacts on population health and climate varies by location. Figure 4.15 presents BUGS emissions as a percentage of all emissions in three large global regions. In each region, total emissions account for the contributions of many sources of pollution, including cars, trucks, power plants, manufacturing plants, wildfires, stoves used for cooking, heating, and fuel-based lighting, to name just a few. As a single source, generators account for a significant fraction of some pollutants but differences in the characteristics of other pollutant sources affecting a region leads to variation in BUGS contributions in the same region, and across different regions. Overall, the contribution of BUGS to pollutant emissions is greatest on the African continent.

Comparing the emissions from BUGS to those of other sources and energy sectors can be useful for determining their importance relative to other mitigation opportunities. **Figure 4.16** presents BUGS emissions as a portion of that from major energy sectors, by pollutant. Sectors are aggregates of many sources of pollution, often grouped by the type of energy services they provide (i.e., transportation, power). **Figure 4.17** presents estimates of absolute pollutant emissions across sectors and regions.

The large contribution of NO_x emissions by BUGS stands out among other pollutants examined here. Across all modeled countries, 1500 kilotons (kt) of NO_x are emitted as a result of backup generation each year. In Africa, this accounts for 7 percent of total NO_x emissions annually, but significantly less in South Asia where vehicle fleets are much larger. In Sub-Saharan Africa, generators account for 15 percent of total NO_x emissions—equivalent to 35 percent of the NO_x from the entire transportation sector. It also accounts for 65 percent of NO_x emitted from power generation in Africa, and more than 10 percent in Asia and the Americas.

Regional emissions of $PM_{2.5}$ and other aerosol species from BUGS are modest in comparison to that of several dominant sectors, but may still be an important source of local pollution. Across all modeled countries, the annual $PM_{2.5}$ emission rate for BUGS is estimated to be 1,000 kt/year, and 400 and 300 kt/year for BC and OC, respectively. Across regions shown in **Figure 4.16,** BUGS contribute 20

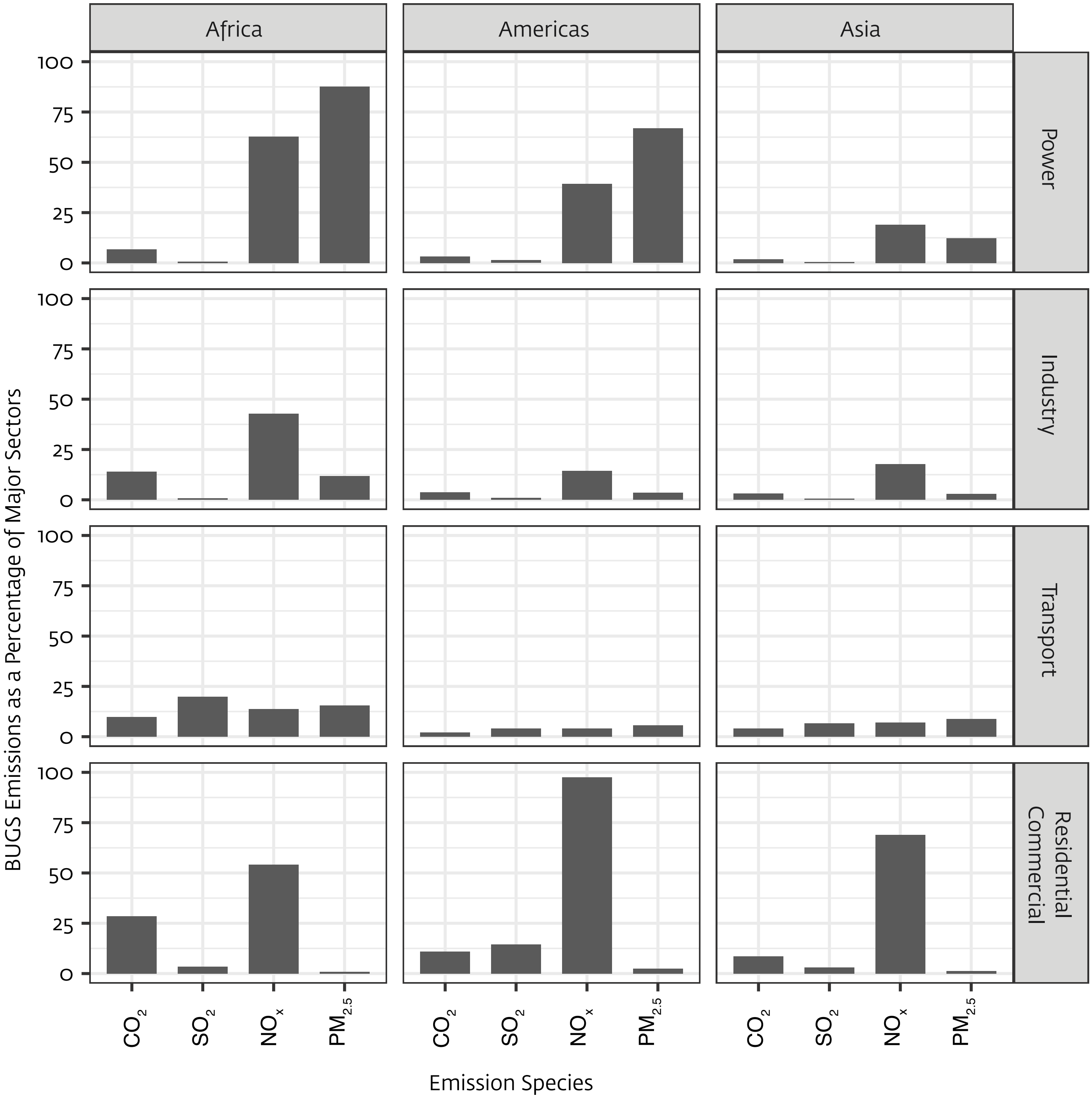
FIGURE 4.15: CONTRIBUTION OF BUGS TO REGIONAL EMISSIONS



to 75 kt of $PM_{2.5}$ emissions per year—equivalent to 5 to 15 percent of transportation emissions. As a major source of energy generation, BUGS account for 10 to 75 percent of $PM_{2.5}$ from the power sector. In urban areas, where the use of solid fuels in homes is typically much lower than indicated by national averages—and where generators are most prevalent—BUGS likely account for a larger fraction of local particulate emissions and air pollution than our results suggest. Several studies of pollutant source contributions in Indian cities found generators to account for as much as 28 percent of local $PM_{2.5}$ pollution.[37]

The fact that emissions from BUGS, an individual source within the Power Sector, can be compared to the emissions of entire sectors is indicative of their likely importance as a pollutant source in some countries. Also, while examining

FIGURE 4.16: EMISSIONS FROM BUGS EXPRESSED AS A FRACTION OF TOTAL SECTORAL EMISSIONS IN 2016

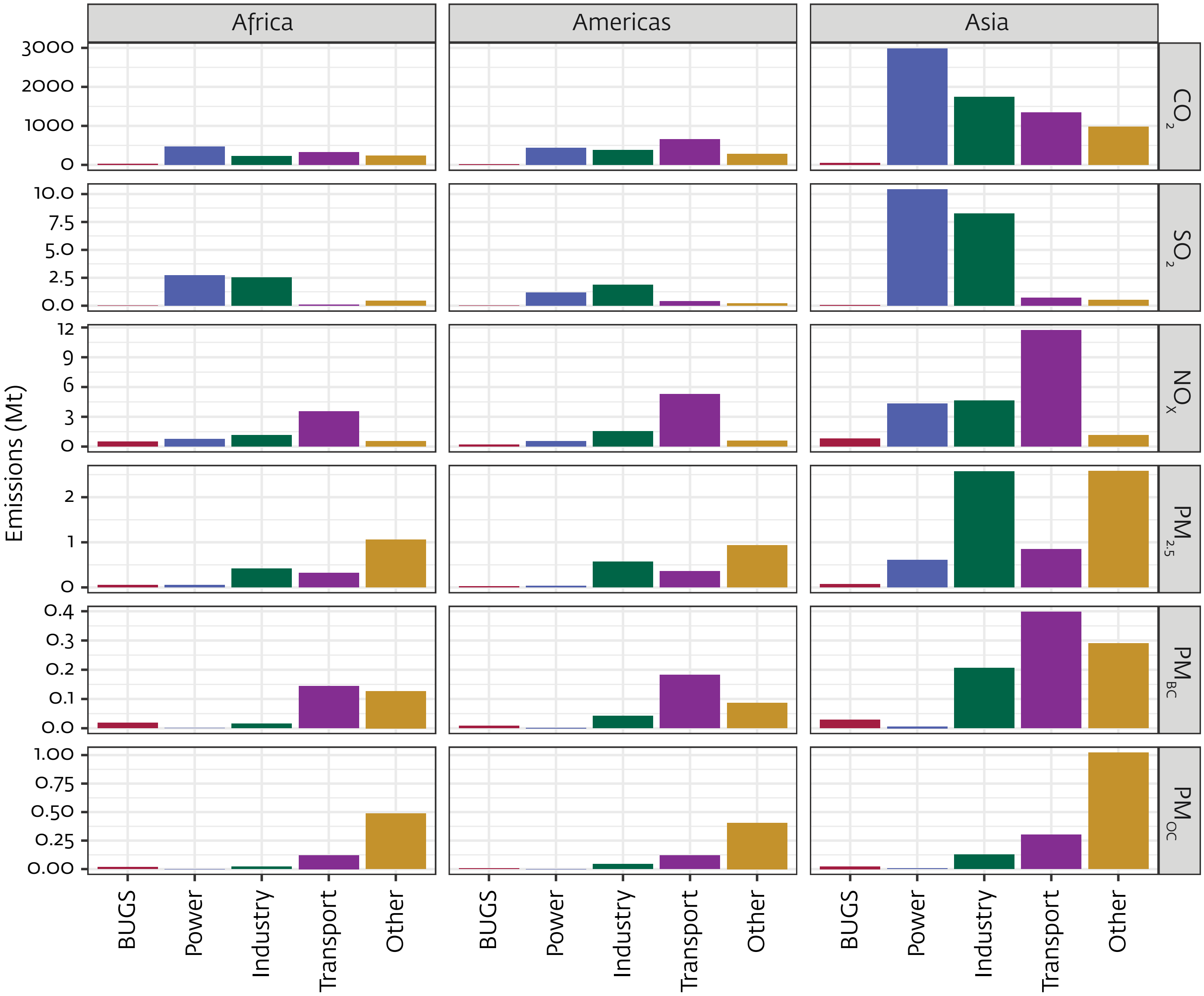


Note that BUGS are an emitting source within the Power Sector, so percentages are interpreted as the fraction of total Power Sector emissions attributable to BUGS.

a pollutant source at coarse geographic scales is useful as a first-approximation of its importance, it can dilute the source's contribution to local burdens, especially when its use is concentrated in small areas. Our results suggest that BUGS are one such source, given that fleets are predominantly deployed in urban areas with grid access.

Likely important but not reported here are the emissions of non-methane volatile organic compounds (NMVOCs) and carbon monoxide. This is particularly relevant for populations employing large numbers of two-stroke gasoline-fueled generators, notably in Nigeria and other parts of West Africa. Measurements of two stroke engines and generators have been reported to emit as much as 40 percent[38] of their fuel as unburned vapor (VOCs) and can generate acutely dangerous concentrations of carbon monoxide.[39] These high emissions of both NMVOCs, in combination with their NO_x emissions, make generators a potentially potent source for promoting ground-level ozone formation,[40] a pollutant associated with numerous respiratory diseases.

FIGURE 4.17: EMISSIONS (MEGATONS (MT)/YEAR) FROM BUGS COMPARED TO SELECTED EMITTING SECTORS, FOR COMPARISON



Note that because BUGS are a source within the Power Sector, their contribution has been subtracted out of the sectoral total to avoid double counting. The residential sector is not shown for presentation purposes but is the dominant source in all regions for particulate matter species.

Table 4.20 summarizes the dimensions of environmental and health risks we identified from generator emissions. Not all of these impact dimensions were directly modeled as part of our research effort, but they are mentioned as they remain important issues. There are risks associated with the pollutants presented, with some at a higher level of certainty than others due to a lack of good quality data on BUGS emission characteristics.

Implications of Data Gaps on Pollutant Emissions and Impact Estimates

Our work revealed that major gaps exist in the understanding of backup generator performance in developing countries, requiring us to apply assumptions that likely bias at least some of our pollutant estimates low. In the absence of data from generators in developing country fleets, we often relied upon lab-based performance data for new generators tested in industrialized countries. These devices are likely better performing than the typical unit used by residents in developing countries to power their homes and businesses. Moreover, performance of energy technologies based on lab tests, especially those affected by duty cycles and sensitive to poor maintenance, often yield better performance indicators than those based on in-field measurements under typical usage conditions. This has been true for several energy service technologies (and major emissions sources) relevant to developing countries, including cookstoves, fuel-based lighting, and automobiles. For some pollutants such as CO_2 and NO_X we expect our results are less sensitive to the lack of context-specific performance data given their formation mechanisms. Other pollutants, including $PM_{2.5}$, BC, SO_2, are likely more affected and so are probably conservatively low. Poor fuel quality can also negatively affect generator performance, and while anecdotal accounts of fuel adulteration are common, we are unable to account for the effect of this on our estimates.

The spatial resolution of our estimates may understate the importance of BUGS as a local source of air pollution. In an effort to provide coverage and consistency across as many countries as possible, we focused our analysis on providing national and regional emission estimates. Our

TABLE 4.20: SUMMARY OF BUGS EMISSIONS FOR POLLUTANTS MODELED IN THIS STUDY

Pollutant	*Potential Scale of Impact from BUGS*	Data Quality	Impact Summary
Carbon Dioxide [CO_2]	*Modest contributor at national and regional scales*	Good	We estimate that 100 (Mt) of CO_2 are emitted each year from generators in modeled countries. In Sub-Saharan Africa, the CO_2 emitted by generators is equivalent to 20 percent of the CO_2 emissions from vehicles in the region.
Particulate Matter, Black Carbon, Organic Carbon [$PM_{2.5}$, BC, OC]	*Modest contributor at national and regional scales. Potentially significant source at local scale*	Low *Limited data on emission characteristics of generators used in key regions.*	In Sub-Saharan Africa, emissions of $PM_{2.5}$ from BUGS is equivalent to **35 percent of the $PM_{2.5}$ emitted from vehicles.** It also contributes the majority of $PM_{2.5}$, BC, and OC from the Power Sector in Sub-Saharan Africa. Many BUGS are used near where people live and work and in densely populated (urban) areas, meaning that a larger fraction of what BUGS emit is likely to be inhaled by people.
Nitrogen Oxides [NO_X]	*Potentially a significant source at national and local scales.*	Good *Limited data on emission characteristics of generators used in key regions.*	BUGS are a potentially significant source of NOx in some countries and regions. We estimate that BUGS account for around **5 percent of all NO_x emissions in developing countries, 7 percent in Africa, and 15 percent in Sub-Saharan Africa.**
Sulfur Dioxide [SO_2]	*Minor source at national and regional scales; potentially important source at local scale.*	Low *Limited data on actual fuel quality. Currently assumes local fuel quality standards.*	Overall emissions of SO_2 from BUGS are minor at national and regional scales. Emissions from generators are equivalent to 50 percent of emissions from transportation in Sub-Saharan Africa, but account for less than 0.5 percent of total emissions in Africa, Asia, and the Americas. BUGS may be an important local driver of exposure, given that major emitting sources tend to exist further from densely populated areas.

fleet analysis, however, indicated that the use of BUGS is highly localized, even within a country, being predominantly used in urban areas with grid connections. Other major sources of pollution are also localized, but not necessarily in the same direction as BUGS. In most developing countries, for example, household air pollution accounts for a major and often dominant fraction of $PM_{2.5}$. The use of solid fuel, however, is more prevalent in rural and off-grid communities, and typically less so in areas where generators are widely deployed. In these instances, generators would likely account for a greater proportion of air pollutants than indicated by national or regional aggregates. Finally, generators are often installed in densely populated areas, and in close proximity to homes and businesses,[41] increasing the likelihood that the pollution they emit is eventually inhaled by people. These finer-level assessments were beyond the scope of this work, but our results underscore the importance of context specific examinations into the operational characteristics and impacts of BUGS at a local (i.e., sub-national, city-level) scale.

COUNTRY-LEVEL ACCURACY AND UNCERTAINTY

The modeling framework we developed was designed to accommodate widely available data on trade and household and business surveys and may not be accurate at the country level where nuances of a local market and use cases are not captured. This is the reason we chose to focus on regional averages in most of the results presented above.

It is possible that in some countries our estimates are lower than reality, particularly in places with significant domestic generator manufacturing and/or untracked imported generators. While our combined approach of estimating fleet sizes using import records and sectoral cross-sectional surveys should address some of these discrepancies, survey data were not always available and not all sectors are represented in surveys. It is expected that in cases with significant untracked trade or domestic production, these adjustments are unlikely to fully capture the true volume and probably result in low fleet counts.

For example, in Nigeria, where we highlighted a particularly well-known generator market in the introductory section to this report, there is reason to believe that not all generator trade is captured in the global trade data. This would lead to undercounting and we attempted to adjust fleet counts using analyses of nationally representative household and business surveys that are publicly available. With these adjustments, we estimate that there are 2.8 million residential and 210 thousand commercial sites with actively used generators, totaling 13 GW overall (two times the installed capacity of power plants on the grid), with $5.4 billion in annual spending on fuel alone. Other estimates previously reported in the press (but not from well-described or in some cases any cited sources) report higher numbers of sites (e.g., 12 million active sites across the country[42]) and spending of "as much as" $17 billion in the industrial sector alone.[43] This may be a case where even the adjusted model approach does not capture the full market, and/or the result of exaggerated or high-side estimates reported in press. The model did, however, identify that Nigeria is clearly a country with a significantly large fleet and higher-than-normal spending and fuel consumption compared to many surrounding and other countries. Regardless, the Nigeria case highlights that country-level results from our study can be taken as indicative, and additional work to understand and engage in local contexts is important in advance of investments or engagement to address the market. For similar reasons, we expect that our estimates for India, Lebanon, Thailand, Brazil, and Malaysia are also conservatively low.

Conclusion

It is early days for replacing BUGS with clean energy technologies such as solar and storage, and this report is an attempt to identify and clarify the welfare and environmental opportunities that could accompany such transitions. Our characterization of BUGS fleet compositions, operations, and pollutant emissions enables greater understanding of the impacts of weak grids. Importantly, it reveals the level of avoidable environmental burdens that can begin to be addressed through actions that lead to a reduced reliance on BUGS.

The global capacity of BUGS is immense—equivalent to 700 to 1000 large power plants, nearly double the capacity of generators powering the entire grid in India. In countries where the grids are especially poor, the energy service provided by BUGS rivals, and sometimes exceeds, power plants on national grids. With annual spending on fuel alone in excess of $40 billion, the heavy reliance on BUGS imposes significant costs on families, businesses, and governments. In Western Africa, there is more spent on the fuel for BUGS than on electricity from the grid each year. Much of the financial cost of BUGS operations is driven by the staggering quantity of fossil fuel they consume, which in some regions of Africa is more than half that used by the entire transportation sector. BUGS contribute to emissions of health and climate damaging pollutants, sometimes significantly, even at regional scales. BUGS are predominantly deployed in grid-connected urban centers, and so likely impose greater impact to local air quality than indicated by our results, given the spatial scale of our analysis. Efforts to refine estimates of operational characteristics, performance, and impacts of BUGS through measurements in areas where they are widely deployed may reveal a significant opportunity to improve public health through replacement.

As the cost of clean technologies continue to fall and the understanding of welfare impacts of BUGS improves, there is an emerging and significant value proposition to replace BUGS. The cost of generated electricity from diesel and petrol generators is not likely to fall dramatically due to any current or near-future technology improvements. As a result, the cost of clean technologies may have already reached a level of parity in some markets—or is not far off. Could distributed clean energy systems replace BUGS and even support the local distribution circuits or regional grids where they are installed? The answers to these and other critically important technology and policy questions will help accelerate clean transitions, but also needs to be informed by a better understanding of local conditions.

Replacing BUGS belongs in the global conversation along with efforts to decarbonize electricity grids, transportation systems, and other sectors of the economy. The sector is far-reaching, and in some countries with particularly poor grids accounts for significant financial burdens. Avoiding the emissions, health impacts, and operational efforts imposed by BUGS represents a potentially significant opportunity to improve the welfare of people who rely on them.

Appendix 1: Methodological Details

GENERATOR BACKGROUND DETAILS

Generator Power Ratings

The power rating of generators is defined in terms of “apparent power” with units of “kilo-volt-amps” (kVA). These ratings are similar to the familiar “real” electrical power rating in “kilowatts” (kW), but with the important distinction that the kVA rating also accounts for the voltage-stabilizing “reactive power” that needs to be provided with generators in standalone operation.

The idea behind reactive power support is that some loads (such as motors, power supplies, and others) have electrical characteristics where they do not just need real power (kW) but also require voltage stabilization to help balance the circuit. This additional work is called “reactive power,” and uses up some capacity of the generator. The combination of real and reactive power is what needs to be supported by a generator overall to serve loads with stable voltage; this is given in terms of kVA.

For most buildings, the level of kVA required from a generator is between 1 and 1.5 times the sum total kW rating of the loads being served.

Fuel Types

Diesel fuel is typically used in generators designed to service larger (greater than 3-5 kW) loads. Diesel fueled generators are generally more efficient than gasoline generators for the same output level. They are sometimes called “compression ignition” generators because of the design of the engines, which take advantage of a property of diesel fuel where the fuel auto-ignites at a sufficiently high pressure. We distinguish three sizes of diesel generators: small (< 75 kVA/60 kW), medium (75–375 kVA, 60–300 kW) and large (> 375 kVA/ > 300 kW). Previously reported estimates of the levelized cost of electricity (i.e., the average cost including buying the generator, fuel, and maintenance) is between 0.20 and 0.30 $/kWh for large diesel generators[44] and $0.20 to $0.50 for smaller units.[45]

Gasoline (petrol) generators service small (less than 3–5 kW) loads, often providing just enough energy to run lights and basic appliances. They are generally less efficient and robust than diesel units, so rated capacities greater than 3 to 5 kW are not common. Gasoline units are powered by either two or four-stroke motors, with two stroke motors being far more affordable but poorer performing. A typical gasoline generator used throughout Nigeria, referred to locally as “I better pass my neighbor,” runs on a two-stroke engine with rated capacity of around 0.5 kW. Given the narrow range of capacities available for gasoline generators, we do not distinguish size categories. Because of lower efficiency than diesel, gasoline generators have a higher levelized cost of electricity, around 0.60 $/kWh.[46]

Note on BUGS costs above vs. Solar: As of 2018, the levelized cost of rooftop PV has fallen to 0.20 $/kWh, with the cost of delivered energy from PV+ storage at 0.40 to 0.70 $/kWh.[47] The projections for future costs of PV and storage suggest continued progress toward a transition point where PV and storage could effectively foreclose on the market for distributed energy currently served by backup generators, depending on the marginal costs of their operations.

User Segments

The loads and utilization characteristics of BUGS may vary across user segments, affecting decisions around the type and size of generator deployed. These application characteristics may also be important in affecting market-driving factors such as affordability and payback duration. Our modeling framework maintains flexibility to distinguish user segments in order to consider these factors.

In all modeled countries, generator fleets are classified into residential or commercial sectors, urban or rural, and on- or off-grid. National surveys often report ownership status of generators, urban/rural designation, and grid connection status, but rarely collect characteristics of the generator units needed to inform fleet disaggregation by type and size. In the absence of these data, a rough apportioning of the fleet to residential or commercial sectors is performed using input from experts in major generator markets and review of backup generator literature. User segments accounting for large portions of fleet deployments have been identified. These include the telecom sector and offshore diesel generators used on barges, for example. We do not explicitly examine these sectors in-depth here, but our methodological approach does account for these units in the electric generator fleet in each country/region.

COSTS OF BACKUP GENERATORS

Capital Investments

Capital costs represent the cost of purchasing BUGS. Fleet size estimates and import rates are used to examine capital costs of BUGS purchased each year and for valuing the replacement cost of the fleet. To estimate the size of fleets, we examine country-level import and export records of generators and combine this information with data on grid reliability to approximate generator runtimes and corresponding lifetimes. Results on the prevalence of generator ownership from an analysis of over 70 nationally representative household[48] and business surveys[49] is used to adjust country-level fleet sizes, with regional adjustment factors applied when country-level surveys are not available.

Fuel and O&M Costs

BUGS provide energy services by burning fossil fuels to generate electricity. Expenditures on fuel are typically the dominant cost associated with their operation. The regular maintenance and servicing of generators, especially for larger capacity units, also have associated costs. We combine estimates of fleet size and composition with estimates of runtime (from country-level SAIDI values) and generator performance curves to estimate fuel consumption. Historic pump prices of fossil fuels are used to convert volumetric consumption of diesel or gasoline to costs. Operation and Maintenance (O&M) costs are not included as a cost in our estimates, but can be considerable in some BUGS applications—conservatively on the order of 10 to 20 percent of the fuel costs in most situations.[50]

EXPENDITURE ON GRID VS. BUGS

When the grid is reliable, the main cost of BUGS is related to capital investment and routine maintenance. In the regions we studied, the grid is very weak. Frequent operations of generators mean that fuel costs can become a significant or dominant expense, thus comparing expenditures on BUGS versus the grid can provide a valuable point of context and is included in some presentations of the results. A recent study of several countries in Africa reported that the reliance on BUGS for electricity generation increases fossil fuel consumption (and associated societal costs for fuel) by a factor of 1.5 to 1000 depending on assumptions about local conditions and the capability of existing grid capacity to satisfy electricity demand.[51] Our approach has a different method for estimating generator costs than that study, using import/export data and more granular information on fleets. Our estimates for expenditures on the grid are based on the cost of electricity and the total energy generated, adjusted for transmission and distribution losses.

Subsidies

The use of BUGS to meet energy service needs is often incentivized and enabled through government subsidies on fossil fuels. Despite the well-intentioned goals of many subsidy schemes, they are often inefficient and incur direct and indirect costs to users, governments, and the environment. These subsidies make alternative pathways to electricity services less competitive by creating artificially low service costs for BUGS. Reducing reliance on generators can ease the burden of subsidies on government budgets, and removing or reducing subsidies could better signal the cost of backup generation to customers who may have other options.

We apply the widely used "price-gap" approach[52] to estimate country-level consumption subsidies and the corresponding cost of subsidizing the fossil fuel used in BUGS. When valuing fossil fuel subsidies, external costs from the impact of combustion products on climate and air quality add additional (and sometimes significant) cost. We do not report on the external cost of subsidies here, but our results provide the information necessary to perform these additional cost calculations.

Health & Environmental Hazards

BUGS are a potentially significant pollutant source, especially at a local scale. In areas where they are deployed, BUGS contribute to the emissions of health and climate damaging pollution. However, it is often difficult to differentiate their contribution from that of cars, trucks, and other technologies that burn the same fuels. As a result, the extent to which mechanisms that reduce their operations could contribute to achieving health and climate goals remains unclear.

To begin to address this impact gap, we estimate the contribution of BUGS to emissions of health and climate relevant pollutants. Our results are used to update a global emissions inventory and comparisons to other pollutant sources and sectors performed at a national and regional scale. While this study does not explicitly examine contributions to outdoor air pollution and exposure, disease, or radiative forcing, it does establish the groundwork and provides the necessary inputs for such assessments for most developing countries in the world. There is limited information on the emission characteristics of generators used in developing countries, leading us to make assumptions that likely result in conservatively low emission estimates for several pollutants of importance to health and the environment. These data gaps and their implications for our results are discussed in the main report and in Appendix 2.

There are also non-pollutant hazards that arise from the operation of BUGS, such as their contribution to noise pollution and accidental injuries. These impacts are likely important, especially at a local scale, but were not examined as part of this study. Exposure to excessive noise contributes to the local burden of disease through increased risk of heart disease, cognitive impairment in children, and loss of sleep, to name a few. A recent study by the World Health Organization estimated that at least one million life years are lost annually due to exposure to traffic noise pollution in Western Europe.[53] Anecdotal accounts of the noise pollution generated by BUGS is widely documented in the gray literature, but no study that we are aware of has examined the potential health implications on local or national populations.

STUDY SCOPE AND METHODOLOGY

This study uses the best available global data sets on BUGS and the drivers of generator use to estimate backup fleet operations and pollutant emissions for 167 countries. This work aims to establish the most comprehensive understanding of the scale of backup generator fleet deployment and operations in developing countries and their contribution to national and regional emissions. Our approach attempts to reflect the mechanism by which grid quality affects reliance on BUGS, and in turn the impact of BUGS on economies and pollutant emissions.

Geographic Scope

This study characterized backup generator operations in 167 countries, representing 94 percent of the population living in low- and middle-income regions of the world, excluding China. **Figure 6.1** provides an overview of the countries modeled as part of this work and their regional categorizations, and **Table 6.1** summarizes the regional populations. For most countries we applied a standardized approach for modeling the backup generator sector based on globally available data sets. For Nigeria and India (the top two markets in terms of total load served by generators) a more customized approach was taken to improve user segmentation and improve the model fidelity. We exclude several developing countries from our analysis due to limited data from which to perform a country-specific analysis when our standardized approach could not be applied. The most notable of these countries is China, which is a major producer of electric generating sets globally.

Country-level results are aggregated over several global region classifications. A sub-classification of World Bank regions is used whenever possible in order to provide more granular representation of Sub-Saharan Africa and several parts of Asia. We use 2018 World Bank income classifications to differentiate between all modeled countries and low- and middle-income countries (LMICS) when presenting results for several backup generator fleet characteristics. Fuel consumption and pollutant emissions from generators are aggregated using country and regional classifications employed by IIASA's Greenhouse Gas-Air Pollution Interaction and Synergies (GAINS) model.[54]

Technological Scope

Our analysis estimates fleet characteristics for diesel and gasoline-fueled electric generating sets. We distinguish three capacity (size) categories for diesel (compression ignition) generators: small (< 75 kVA, < 60 kW), medium (75–375 kVA, 60–300 kW) and large (> 375 kVA, > 300 kW). All gasoline (spark ignition) generators are aggregated into single group. Our analysis is exclusive to electric generating sets and excludes direct drive generators for agricultural and industrial applications.

Methodological Overview

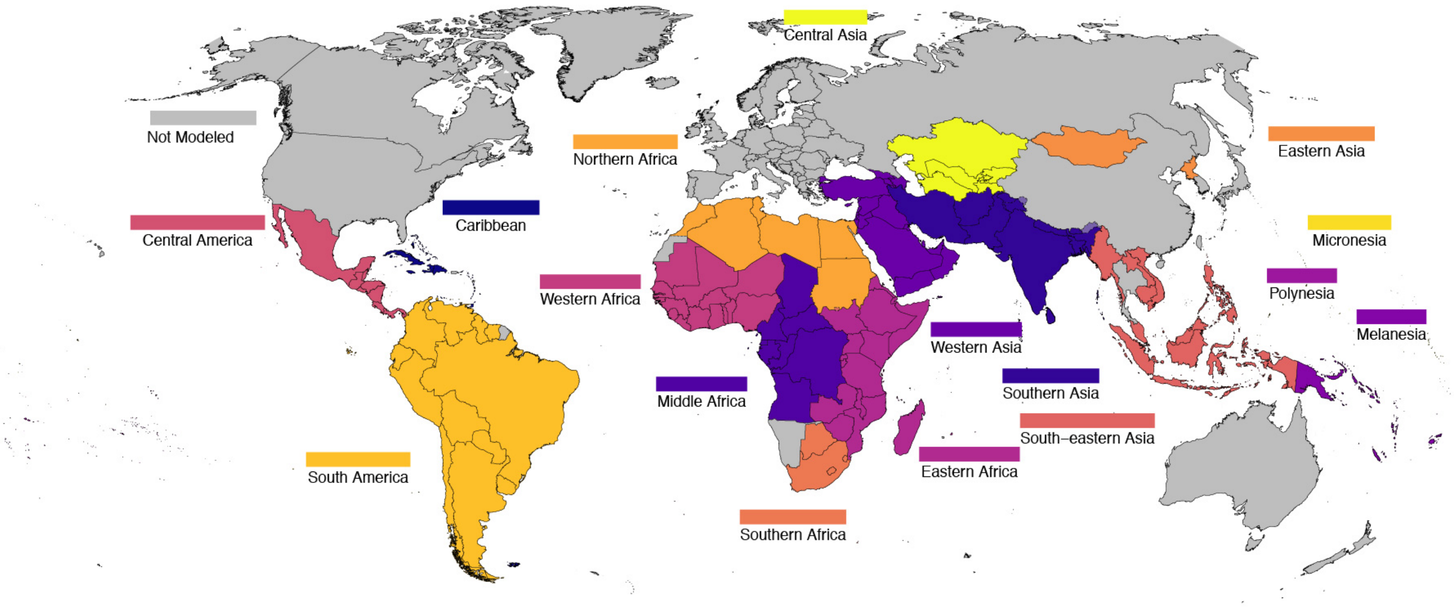
The framework we employed uses existing data on generator sales, ownership prevalence, grid reliability, and generator performance characteristics to estimate various fleet characteristics and their impacts of operation. Resulting impact estimates are directly linked to the level of service provided by BUGS and the reliability of the grids they compensate for. The first-order modeling approach emphasizes impacts that directly relate to the consumption of and expenditure on fuels and generating units, as determined by utilization characteristics.

Global import/export trade data on generators and national surveys were used to estimate the number of generators used in 167 developing countries (fleet size), classified by fuel type (i.e., diesel, gasoline) and their size (maximum power output) categories. In most countries (except India and Nigeria) we did not attempt to account for domestically produced generators, which is a known source of conservative bias in our approach. The total duration of power outages (i.e., system average interruption duration index, or SAIDI) were the basis for the **hours of BUGS operation (runtime);** this was combined with manufacturer data about their **efficiency and assumptions about loading factor** of generators to estimate **energy generation** and **fuel consumption.** Fuel consumption results were used to update a widely used fuel and **emissions** inventory[55] in order to estimate the contribution of BUGS to fossil fuel demand and emissions of health and climate damaging pollutants. Fuel estimates were compared to IEA statistics for the power and commercial sectors and adjusted so that the overall energy use is consistent with IEA. We examine the factors affecting uncertainty in our results and discuss the implications of these results on future efforts to address major knowledge gaps.

TABLE 6.1: SUMMARY OF COUNTRIES MODELED, AND THEIR POPULATIONS AGGREGATED ACROSS WORLD BANK REGIONS

World Bank Region	Number of Countries Modeled (LMICs Only)	Population Of Modeled Countries (Millions)
East Asia & Pacific	29 (22)	607
Europe & Central Asia	10 (9)	167
Latin America & Caribbean	39 (24)	634
Middle East ("Western Asia") & North Africa	20 (13)	436
South Asia	8 (8)	1766
Sub-Saharan Africa	47 (46)	1030
Other	14 (0)	0.86
Total	**167 (122)**	**4642**

FIGURE 6.1: GEOGRAPHIC SCOPE OF THIS STUDY AND DETAILED REGIONAL CLASSIFICATIONS



ANALYSIS METHODS

Overview

Our first-order modeling approach emphasized impacts that directly relate to the consumption and expenditure on fuels and generating units, as determined by utilization characteristics. It is based on a variety of existing and assembled data sets, including global trade records, national surveys, reported grid reliability (SAIDI), and generator performance characteristics. Fuel estimates were used to update inventories within IIASA's Greenhouse Gas-Air Pollution Interaction and Synergies (GAINS) model to estimate emissions and facilitate comparison across other sources and sectors.

To the extent possible, it was important that our approach reflect the connection between energy services from BUGS and grid performance with their downstream impacts. To provide relevant national level insights, we rely upon as many country-level data sets as possible to inform fleet sizes, sectoral allocations, and generator runtimes while still maintaining a consistent procedure across all countries. Our bottom-up approach differs from many previous efforts to size backup generator service and impacts in that we do not begin with the assumption that power plants on the grid, even if reliable, reflect electricity demand.

The fuel consumption, A, of generators using fuel type, k, in country i can be described as:

$$A_{i,k}=\sum{}_{g}N_{i,k,g}P_{i,k,g}T_{i}CF_{k,g}BR_{k,g} \tag{1}$$

Where $N_{i,k,g}$ represents the number of generators in country i using kth fuel of the gth size (capacity) category. We distinguish three size categories for diesel generators and one size category for gasoline generators. $P_{g,k}$ is the average rated power output of a generator in size category g, informed by review of literature and discussion with generator distributors. T_k is the average runtime of a generator based on SAIDI values calculated at the national level or based on regional averages in the minority of instances where country-level estimates were not available. $CF_{k,g}$ is the fraction of the rated capacity that is utilized when operated (capacity factor). The product of parameters up to this point yields an estimate of energy generation of generators (i.e. kWh). $BR_{k,g}$ is the average fuel consumption rate, calculated from fuel consumption curves to account for differences and dependencies on generator type, size categories, and output levels.

For modeled simulations, parameters in Eq.1 were allowed to vary around distribution parameters informed by results from underlying analyses, literature review, and consultations with generator industry experts. Note that our framework also maintains flexibility to account for differences across user segment, grid access, and urban status.

In nearly all instances, however, there was inadequate data to account for differences in performance and operational parameters at such a granular segmentation scale. Thus, generator operation characteristics are assumed to be the same across these classifications within a country.

Several impacts are calculated from fuel consumption (activity) estimates. For example, annual fuel consumption multiplied by an emission factor (EF) for nitrogen dioxide, yields the nitrogen dioxide emission rate; multiplying diesel consumption by the local pump price yields an estimate of annual expenditure on fuel for BUGS.

The framework for estimating emissions from generators can be generally expressed as:

$$E_{i,p}=\sum_k \sum_m A_{i,k,} EF_{i,k,m,p} X_{i,k,m,p} \qquad (2)$$

where i, k, m, p respectively represents the country, fuel type, abatement measure, and pollutant. $E_{i,p}$ is the emissions of pollutant p in country i, and Ai,k the activity level of fuel type k estimated in Eq 1. $EF_{i,k,m,p}$ is the pollutant emission factor of pollutant p, of fuel type k, in country i, after application of control measure M. $X_{i,k,m,p}$ is the share of total activity of type k in country i which control measure m for pollutant p is applied. For calculating baseline emissions, we apply default emission factors and control measures from GAINS described in Klimont et al. (2017).[56]

Generator Runtimes

Generator runtimes were based on SAIDI values calculated from an analysis of the World Bank Enterprise Surveys and the World Bank Doing Business Surveys. SAIDI values reflect the hours of grid outage per year experienced by the average customer. For consistency, we apply 2016 values of SAIDI, based on data from that survey year, or based on modeled trends. SAIDI was assigned at the country-level, based on country-specific data or regional trends if country data were not available.

Data Sources

Data sources used for each country are described in **Table 6.2**

Doing Business Report

Estimates from the World Bank Doing Business Report, specifically the Getting Electricity indicator set, were also used to estimate grid outage. Starting in 2015 the indicator set includes country level estimates of SAIDI as well as other electrical grid reliability metrics. For some countries, reliability metrics are reported for two cities, and in these cases the average of the two cities was calculated and used to represent the nation. Doing Business surveys are representative of the country's largest economic center and are therefore not nationally representative. To account for this, we adjusted SAIDI estimates from Doing Business Surveys with a scaling factor based on a comparison of SAIDI for countries sampled in both Doing Business and Enterprise Surveys.

SAIDI Estimation

Due to differences in data availability for each of the countries for which SAIDI is estimated, multiple estimation methodologies have been implemented. Each of the possible methodologies for generating an estimate of SAIDI in each country is described below.

Average EID from Enterprise Surveys

If a country has Enterprise Survey data for the year 2016, the average EID from firms surveyed is used as the SAIDI estimate. For the purposes of representing the uncertainty in this estimate the standard error is also calculated. The World Bank Enterprise Surveys are firm-level surveys conducted through interviews with business owners and managers. Results from the enterprise survey were used to calculate an Experienced Interruption Duration (EID) for each firm. The EID is defined as the number of hours of outage experienced by the firm in the survey year and when averaged, interpreted as the SAIDI value.

Country Level GEE model

If a country had Enterprise Survey data for at least two years but neither were from 2016, a 2016 SAIDI value was estimated using a Generalized Estimating Equation (GEE) model. The GEE model estimated SAIDI as a function of year using the EID for each firm in the country as an input. All observations from the same location listed in the Enterprise Survey (usually cities) were treated as independent. This model was then used to estimate SAIDI in the country for the year 2016. The standard error was also calculated from the GEE model to represent the uncertainty in the SAIDI estimate.

Scaled Doing Business Survey

This approach was applied if a country had one or fewer years of Enterprise Survey data available (not 2016) but a SAIDI estimate available from the World Bank Doing Business Report, specifically the Getting Electricity indicator set. Starting in 2015 the indicator set included country-level estimates of SAIDI as well as other electrical grid reliability metrics based on interviews with utility companies. Doing Business surveys are representative of the country's largest economic centers and are therefore not nationally representative and reflect a different sampling frame than the Enterprise Surveys. As a result, Doing Business SAIDI values were adjusted using results from a regression model of SAIDI values from Doing Business and Enterprise Surveys, where there was country overlap. In all instances, this adjustment increased SAIDI. Three data points were thrown out as outliers due to high estimates of SAIDI from Getting Electricity (South Sudan, Honduras, and eSwatini).

Country Enterprise Survey Scaled With Regional SAIDI Trend

This approach was used if a country had one year of data from the Enterprise Surveys that was not in 2016 and no available data from Doing Business. A regional level GEE model was used to estimate the average change in SAIDI as a function of time for a region, then used to estimate the 2016 EID for the country. All observations from the same location listed in the Enterprise Survey (usually cities) were treated as independent. The regions used are the UN regions with the exception of Oceania; the three UN Regions (Polynesia, Melanesia and Micronesia) are combined and treated as one region due to limited data availability. This trend in SAIDI was used to extrapolate from the SAIDI value calculated from the one year that Enterprise Data was available for the country. To represent the uncertainty in this estimate, the standard error was calculated based on the regional SAIDI trend.

Regional Level GEE model

If no country data on SAIDI were available, a regional-level average was applied based on results from a GEE model for that region. The defined regions are consistent with the UN regions with the exception of Oceania which is a combination of three UN regions (Polynesia, Melanesia and Micronesia). All observations from the same location listed in the Enterprise survey (usually cities) are treated as a dependent.

TABLE 6.2: COUNTRIES MODELED AND CORRESPONDING DATA SOURCES USED TO INFORM ESTIMATES OF FLEET SIZE AND COMPOSITION

NOTES AND REFERENCES

C	United Nations Statistical Division COMTRADE 2005–2016; Atlas of Economic Complexity[57]
E	World Bank Enterprise Surveys[58]
D	USAID Demographic and Health Surveys[59]
L	World Bank Living Standards Measurement Study Household Survey[60]
I	Telecom Base Transceiver Stations count[61]
NT	GSMA "Powering Telecoms: West Africa Market Analysis" (2013)[62]
NO	World Bank "Diesel Power Generation Inventories and Black Carbon Emissions in Nigeria" (2004)[63]

Country ISO	Country Name	Region	Reference
AFG	Afghanistan	Southern Asia	C, E, D
DZA	Algeria	Northern Africa	C
ASM	American Samoa	Polynesia	C
AGO	Angola	Middle Africa	C, E, D
AIA	Anguilla	Caribbean	C
ATG	Antigua and Barbuda	Caribbean	C, E
ARG	Argentina	South America	C, E
ARM	Armenia	Western Asia	C, E
ABW	Aruba	Caribbean	C
AZE	Azerbaijan	Western Asia	C, E
BHS	Bahamas	Caribbean	C, E
BHR	Bahrain	Western Asia	C
BGD	Bangladesh	Southern Asia	C, E, D
BRB	Barbados	Caribbean	C, E
BLZ	Belize	Central America	C, E
BEN	Benin	Western Africa	C, E, D
BTN	Bhutan	Southern Asia	C, E
BOL	Bolivia	South America	C, E
BWA	Botswana	Southern Africa	C, E
BRA	Brazil	South America	C, E
VGB	British Virgin Islands	Caribbean	C
BRN	Brunei Darussalam	South-Eastern Asia	C
BFA	Burkina Faso	Western Africa	C, E
BDI	Burundi	Eastern Africa	C, E
KHM	Cambodia	South-Eastern Asia	C, E
CMR	Cameroon	Middle Africa	C, E, D
CPV	Cape Verde	Western Africa	C, E
CYM	Cayman Islands	Caribbean	C
CAF	Central African Republic	Middle Africa	C, E
TCD	Chad	Middle Africa	C, E
CHL	Chile	South America	C, E
COL	Colombia	South America	C, E
COM	Comoros	Eastern Africa	C
COK	Cook Islands	Polynesia	C
CRI	Costa Rica	Central America	C, E

Country ISO	Country Name	Region	Reference
CIV	Côte d'Ivoire	Western Africa	C, E
CUB	Cuba	Caribbean	C
CUW	Curaçao	Caribbean	C
CYP	Cyprus	Western Asia	C
PRK	Democratic People's Republic of Korea	Eastern Asia	C
COD	Democratic Republic of the Congo	Middle Africa	C, E, D
DJI	Djibouti	Eastern Africa	C, E
DMA	Dominica	Caribbean	C, E
DOM	Dominican Republic	Caribbean	C, E, D
ECU	Ecuador	South America	C, E
EGY	Egypt	Northern Africa	C, E
SLV	El Salvador	Central America	C, E
GNQ	Equatorial Guinea	Middle Africa	C
ERI	Eritrea	Eastern Africa	C, E
ETH	Ethiopia	Eastern Africa	C, E, L
FLK	Falkland Islands	South America	C
FSM	Federated States of Micronesia	Micronesia	C, E
FJI	Fiji	Melanesia	C, E
PYF	French Polynesia	Polynesia	C
ATF	French Southern and Antarctic Lands	Seven seas (open ocean)	C
GAB	Gabon	Middle Africa	C, E, D
GEO	Georgia	Western Asia	C, E
GHA	Ghana	Western Africa	C, E, D
GRD	Grenada	Caribbean	C, E
GUM	Guam	Micronesia	C
GTM	Guatemala	Central America	C, E
GIN	Guinea	Western Africa	C, E
GNB	Guinea-Bissau	Western Africa	C, E
GUY	Guyana	South America	C, E, D
HTI	Haiti	Caribbean	C
HND	Honduras	Central America	C, E
IND	India	Southern Asia	E, D, I
IDN	Indonesia	South-Eastern Asia	C, E
IRN	Iran	Southern Asia	C
IRQ	Iraq	Western Asia	C, E, L
ISR	Israel	Western Asia	C, E
JAM	Jamaica	Caribbean	C, E
JOR	Jordan	Western Asia	C, E
KAZ	Kazakhstan	Central Asia	C, E
KEN	Kenya	Eastern Africa	C, E
KIR	Kiribati	Micronesia	C
KWT	Kuwait	Western Asia	C
KGZ	Kyrgyzstan	Central Asia	C, E
LAO	Lao People's Democratic Republic	South-Eastern Asia	C, E
LBN	Lebanon	Western Asia	C, E
LSO	Lesotho	Southern Africa	C, E, D

Country ISO	Country Name	Region	Reference
LBR	Liberia	Western Africa	C, E, D
LBY	Libya	Northern Africa	C
MDG	Madagascar	Eastern Africa	C, E
MWI	Malawi	Eastern Africa	C, E, L
MYS	Malaysia	South-Eastern Asia	C, E
MDV	Maldives	Southern Asia	C
MLI	Mali	Western Africa	C, E
MHL	Marshall Islands	Micronesia	C
MRT	Mauritania	Western Africa	C, E
MUS	Mauritius	Eastern Africa	C, E
MEX	Mexico	Central America	C, E
MNG	Mongolia	Eastern Asia	C, E
MSR	Montserrat	Caribbean	C
MAR	Morocco	Northern Africa	C, E
MOZ	Mozambique	Eastern Africa	C, E
MMR	Myanmar	South-Eastern Asia	C, E
BES	Bonaire, Sint Eustatius and Saba	Caribbean	C
MYT	Mayotte	Eastern Africa	C
TKL	Tokelau	Polynesia	C
TUV	Tuvalu	Polynesia	C
NRU	Nauru	Micronesia	C
NPL	Nepal	Southern Asia	C, E
NCL	New Caledonia	Melanesia	C
NIC	Nicaragua	Central America	C, E
NER	Niger	Western Africa	C, E, L
NGA	Nigeria	Western Africa	C, E, L, NO, NT
NIU	Niue	Polynesia	C
MNP	Northern Mariana Islands	Micronesia	C
OMN	Oman	Western Asia	C
PAK	Pakistan	Southern Asia	C, E
PLW	Palau	Micronesia	C
PSE	Palestine	Western Asia	C
PAN	Panama	Central America	C, E
PNG	Papua New Guinea	Melanesia	C, E
PRY	Paraguay	South America	C, E
PER	Peru	South America	C, E, D
PHL	Philippines	South-Eastern Asia	C, E
QAT	Qatar	Western Asia	C
COG	Republic of Congo	Middle Africa	C, E
RWA	Rwanda	Eastern Africa	C, E
SHN	Saint Helena	Western Africa	C
KNA	Saint Kitts and Nevis	Caribbean	C, E
LCA	Saint Lucia	Caribbean	C, E
VCT	Saint Vincent and the Grenadines	Caribbean	C, E
BLM	Saint-Barthélemy	Caribbean	C

Country ISO	Country Name	Region	Reference
WSM	Samoa	Polynesia	C, E
STP	São Tomé and Principe	Middle Africa	C
SAU	Saudi Arabia	Western Asia	C
SEN	Senegal	Western Africa	C, E
SYC	Seychelles	Eastern Africa	C
SLE	Sierra Leone	Western Africa	C, E, D
SXM	Sint Maarten	Caribbean	C
SLB	Solomon Islands	Melanesia	C, E
SOM	Somalia	Eastern Africa	C
ZAF	South Africa	Southern Africa	C, E
SGS	South Georgia and South Sandwich Islands	Seven seas (open ocean)	C
SSD	South Sudan	Eastern Africa	C, E
LKA	Sri Lanka	Southern Asia	C, E
SDN	Sudan	Northern Africa	C, E
SUR	Suriname	South America	C, E
SWZ	Swaziland	Southern Africa	C, E
SYR	Syria	Western Asia	C
TWN	Taiwan, China	Eastern Asia	C
TJK	Tajikistan	Central Asia	C, E, L
TZA	Tanzania	Eastern Africa	C, E, D
GMB	The Gambia	Western Africa	C, E
TLS	Timor-Leste	South-Eastern Asia	C, E, L
TGO	Togo	Western Africa	C, E
TON	Tonga	Polynesia	C, E
TTO	Trinidad and Tobago	Caribbean	C, E
TUN	Tunisia	Northern Africa	C, E
TUR	Turkey	Western Asia	C, E
TKM	Turkmenistan	Central Asia	C
TCA	Turks and Caicos Islands	Caribbean	C
UGA	Uganda	Eastern Africa	C, E, L
ARE	United Arab Emirates	Western Asia	C
URY	Uruguay	South America	C, E
UZB	Uzbekistan	Central Asia	C, E
VUT	Vanuatu	Melanesia	C, E
VEN	Venezuela	South America	C, E
VNM	Vietnam	South-Eastern Asia	C, E
WLF	Wallis and Futuna Islands	Polynesia	C
ESH	Western Sahara	Northern Africa	C
YEM	Yemen	Western Asia	C, E, D
ZMB	Zambia	Eastern Africa	C, E
ZWE	Zimbabwe	Eastern Africa	C, E, D

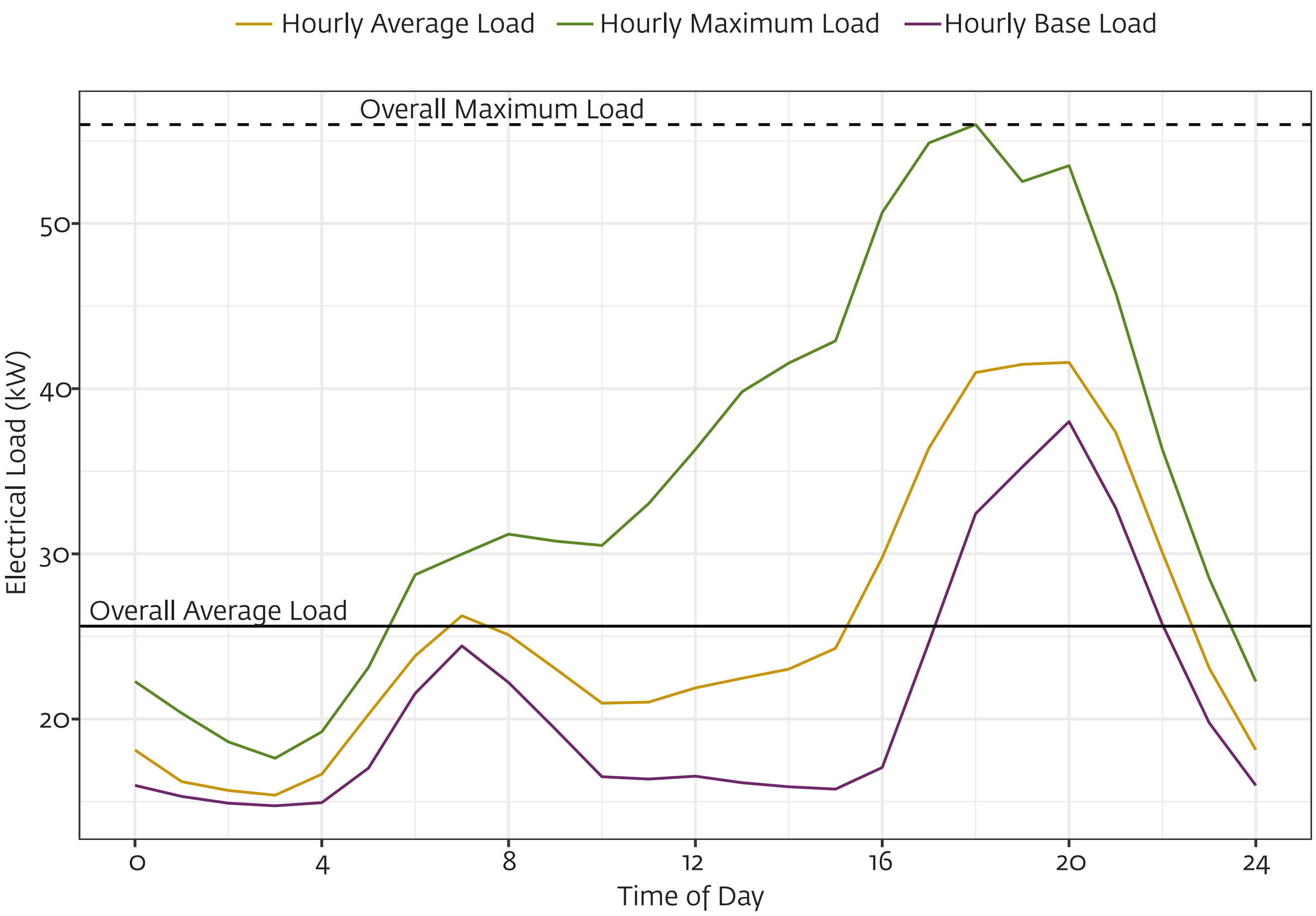
Capacity Factor

We use the term capacity factor to mean the average power output of a generator during operation divided by its rated power output. Another interpretation is that it is the portion of the maximum power output of a generator that is provided, on average. A capacity factor of 0.5 indicates that the generator would, on average, provide half of its maximum rated power output. Within the BUGS workflow, the capacity factor is used in the estimates of energy generation, and thus affects fuel consumption and all resulting impacts downstream of this (for more detail on derivation of fuel consumption rates, see the "Fuel Consumption Rates" document).

To inform our estimate of capacity factor we used a data set containing smart meter data from over 60,000 commercial buildings in California. We assumed that the peak power demand at each building was a proxy for nameplate capacity of the backup generator. Next, we calculated the average electrical demand for each building. Finally, we divided the average electrical demand by the inferred nameplate capacity of the backup generator to arrive at an estimated capacity factor for each building.

Figure 6.2 illustrates components from the building load curve used to estimate the average capacity factor of a generator. The figure depicts the hourly average, max, and min load of a building for each hour of the day. The dotted line (Overall Maximum Load) is taken as the rated capacity of the backup generator and the solid black line (Overall Average Load) is taken as the average power output of the generator. Using these values, capacity factor is calculated as *Overall Average Load / Overall Maximum Load*. If, in reality, the generator is drastically oversized so that the maximum load is significantly smaller than the actual rated capacity, this approach will yield an overestimate of the capacity factor.

FIGURE 6.2: ESTIMATING GENERATOR CAPACITY FACTOR FROM BUILDING LOAD PROFILES



The average capacity factor for California commercial buildings was around 0.3 (30 percent). For the purposes of the BUGS model this value served as the mode of a triangular distribution of capacity factors used in Monte Carlo simulations. The lower and upper bounds of the distribution were assumed to be 0.2 and 0.8, respectively. The average value drawn from this distribution was approximately 0.45 across all model runs. A right skewed distribution was used to account for the possibility that users would purchase a generator that would only be able to support base loads (i.e., the generator may be sized such that load shedding is necessary during grid outages), making the necessary generator capacity much lower and increasing the capacity factor.

FUEL CONSUMPTION CURVES

We estimated fuel consumption rates (liters/kWh) from fuel curves generated from a linear regression of hourly fuel consumption rates (liters/hour) on generator power output (kW). A database containing hourly consumption rates and corresponding generator power outputs was assembled from a review of 73 manufacturer specification sheets of currently manufactured units. A separate linear regression was performed for each of the four generator categories. The generator fuel curve slope is in units of liters per kWh (liters/kWh).

Figure 6.3. shows generator fuel consumption curves applied in the BUGS modeling framework. Each point represents one operating point for a generator, meaning that one generator model may be represented by multiple points (up to 4) on the graph. Individual data points are taken from performance specification sheets of currently manufactured generators. Solid vertical lines represent the median output of a generator in each category based on simulated runs that vary the average generating capacity of a generator and its operating capacity factor. Ninety

FIGURE 6.3: GENERATOR FUEL CONSUMPTION CURVES THE FOUR GENERATOR CATEGORIES CONSIDERED IN THE BUGS MODELING FRAMEWORK

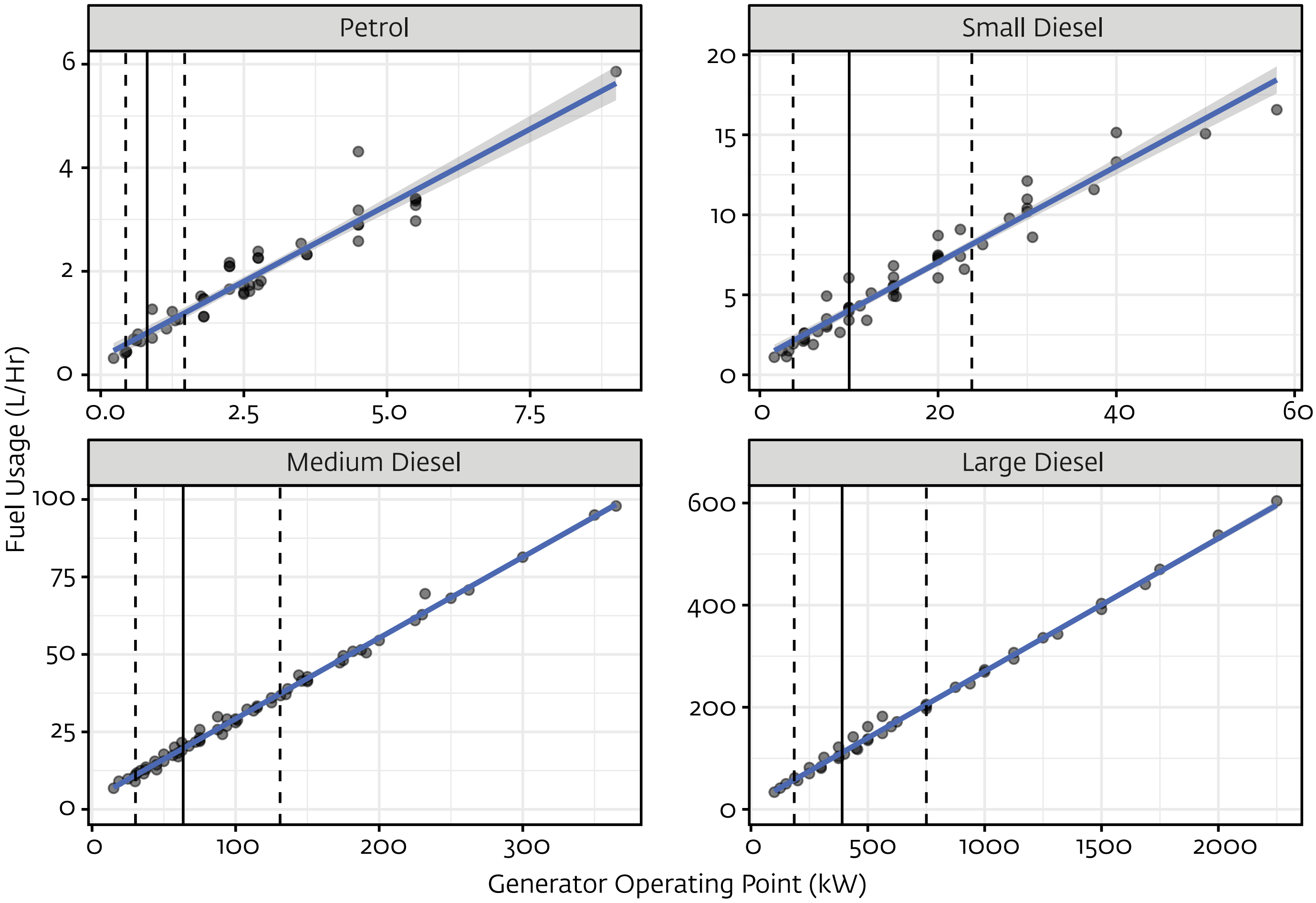
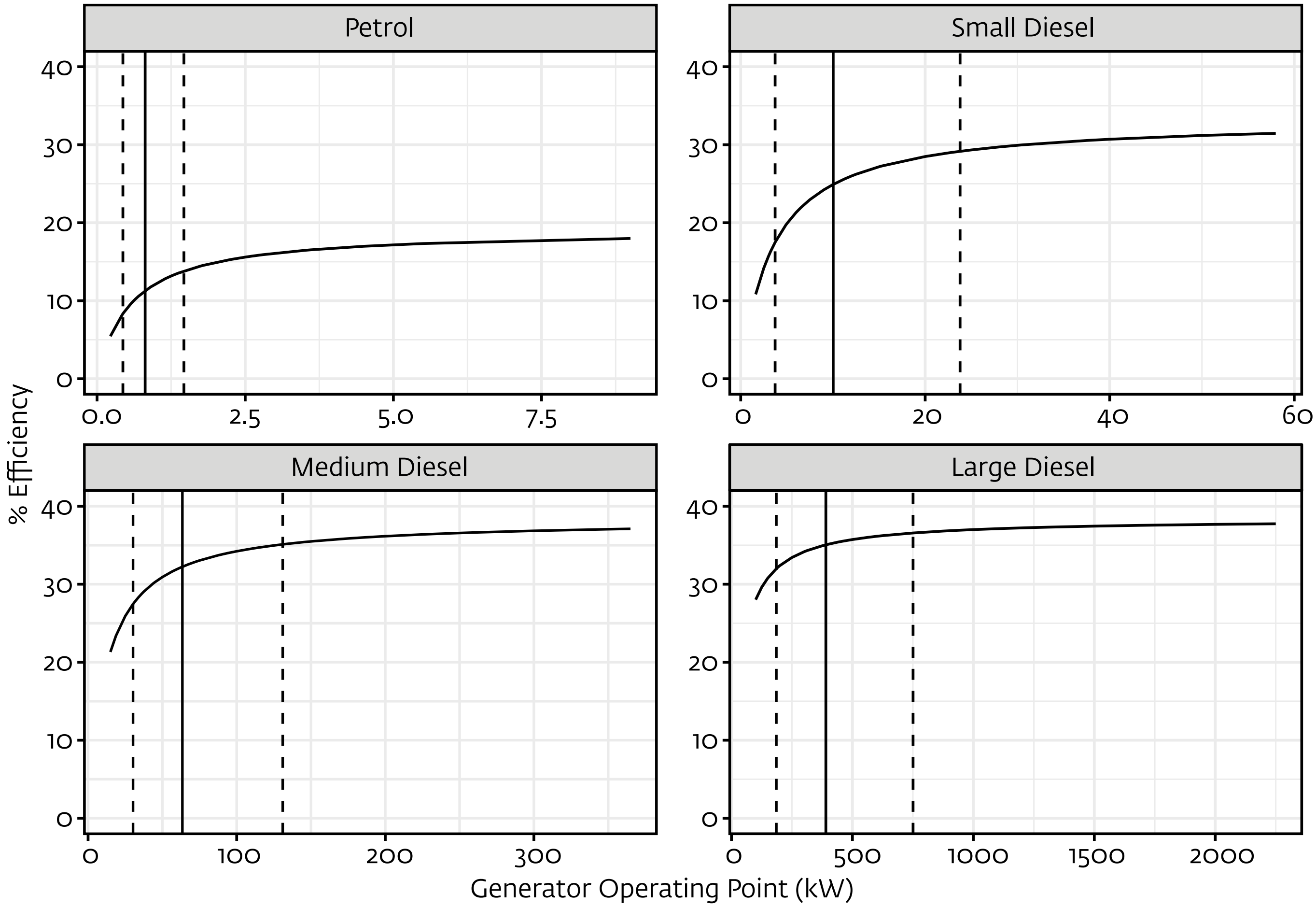


FIGURE 6.4: IMPLIED EFFICIENCY CURVES FOR THE FOUR GENERATOR CATEGORIES USED IN THIS STUDY



percent of modeled estimates fall within the dashed lines (90 percent confidence interval).

Implied Efficiency Curves

In general, the efficiency of a generator changes depending on the electrical load relative to its maximum output. Over the operational range of a generator, its efficiency may vary by as much as 35 percent, being lowest near the bottom end of its operating range. However, while the effect of changing capacity factor on operating point does result in changes in efficiency, it does not decrease overall fuel usage. This is because the dominating factor affecting fuel usage is energy generated—given the same runtime, a higher capacity factor always leads to more energy generation and fuel usage. If a generator is running a small load (low capacity factor) it delivers a relatively small amount of energy at a lower efficiency. The same generator running a larger load (high capacity factor) delivers much more energy at a slightly improved efficiency. **Figure 6.4** presents implied efficiency curves estimated from the modeled relationships shown in **Figure 6.4** combined with heating values for respective fuels.

Figure 6.4. shows the implied efficiency curves for the four generator categories in the BUGS modeling framework. Solid vertical lines represent the median output of a generator in each category based on simulated runs that vary the average generating capacity of a generator and its operating capacity factor. Ninety percent of modeled estimates fall within the dashed lines (90 percent confidence interval). To calculate efficiency, hourly fuel consumption rates are converted to power assuming a heating value for gasoline (32 MJ/liter) and diesel (36 MJ/liter).

UNCERTAINTY ANALYSIS

An in-depth uncertainty analysis was performed using Sobol uncertainty decomposition with Mauntz estimators (Pujol et al. 2017). Our approach applies procedures outlined in Sobol and Saltelli (Saltelli et al. 2010; Sobol et al. 2007) and has been applied widely in the systems modeling literature (Saltelli et al. 2008). The specific computational algorithm was selected for its ability to accurately calculate small first and total order indices (Pujol et al. 2017; Sobol et al. 2007). Another benefit of this algorithm is that it can simultaneously calculate both first and total order Sobol indices.[64]

Sobol first-order indices represent the reduction in output variance which would occur if the variable were to be fixed to a single value. They represent the amount of output variance which would be present if all variables were fixed except the variable in question (Saltelli et al. 2010). For this reason, first-order indices sum to one, as if all variables were fixed to single values there would be no output variance (100 percent reduction).

Due to the large number of variables used within our model, Sobol indices were calculated for variable categories. This reduces computation time and accuracy of indices due to the reduction in dimensionality. These groupings also allow each of our inputs to be independently sampled, which is an assumption requirement of the procedure. Variables are grouped into three categories: Fleet Characteristics, Generator Characteristics, and Runtime. Each category represents the combined influence of up to 32 individual input parameters and is applied at the country and generator fuel type levels.

SUBSIDIES

Implied unit subsidies for both gasoline and diesel fuels are estimated using the price gap approach, a widely implemented method of determining post-tax consumer subsidies. This implied subsidy is estimated as the difference between the domestic consumer (pump) price and the international spot price, adjusting for transportation, distribution, and retailing costs. Informed by previous applications of this approach, this adjustment is assumed to be $0.20 per liter for oil importing/net zero countries and zero for oil exporting countries (Davis 2014, IMF 2013).[65]

We used historic consumer pump prices for diesel and gasoline freely available through World Bank data banks (World Bank, 2018). Oil market status was determined using crude oil imports and exports from UN Comtrade International Trade Statistics Database (Center for International Development at Harvard University). International spot prices were taken from EIA databases (EIA, 2018).

Total subsidy cost for fuel used in BUGS is calculated at a national level using the estimated united subsidy per liter estimated above, and the estimated fuel usage for the same country from our model. For the purpose of this analysis we only consider consumer subsidies. Several countries modeled by BUGS did not have subsidies calculated (27 percent) as domestic consumer price data were not available. However, these countries represent a small portion of total BUGS fuel consumption and would likely have little impact on the total subsidy value.

Appendix 2: Opportunities to Reduce Uncertainty in Estimates

As with many distributed energy systems, significant gaps in the understanding of backup generator use and performance characteristics exist, affecting the precision and accuracy of final impact estimates.It was important that this work consider, to the extent possible, how these gaps contributed to the uncertainty of final results, and use this insight to provide data-driven recommendations for informing future research and market intelligence efforts. We identify that there is both uncertainty resulting from an attempt to apply a consistent modeling approach across countries, and also uncertainty in the parameters of our model arising from data gaps. Overall, these assumptions have likely resulted in conservatively low estimates in most countries and regions.

This Appendix describes the implications of our results on strategies for improving understanding and reducing the uncertainty based on generator type (gasoline or diesel) and location. As a result, the strategies and measurements to address areas of greatest need are differentiated depending on the types of generators deployed and the population in question.

MODEL UNCERTAINTY DECOMPOSITION

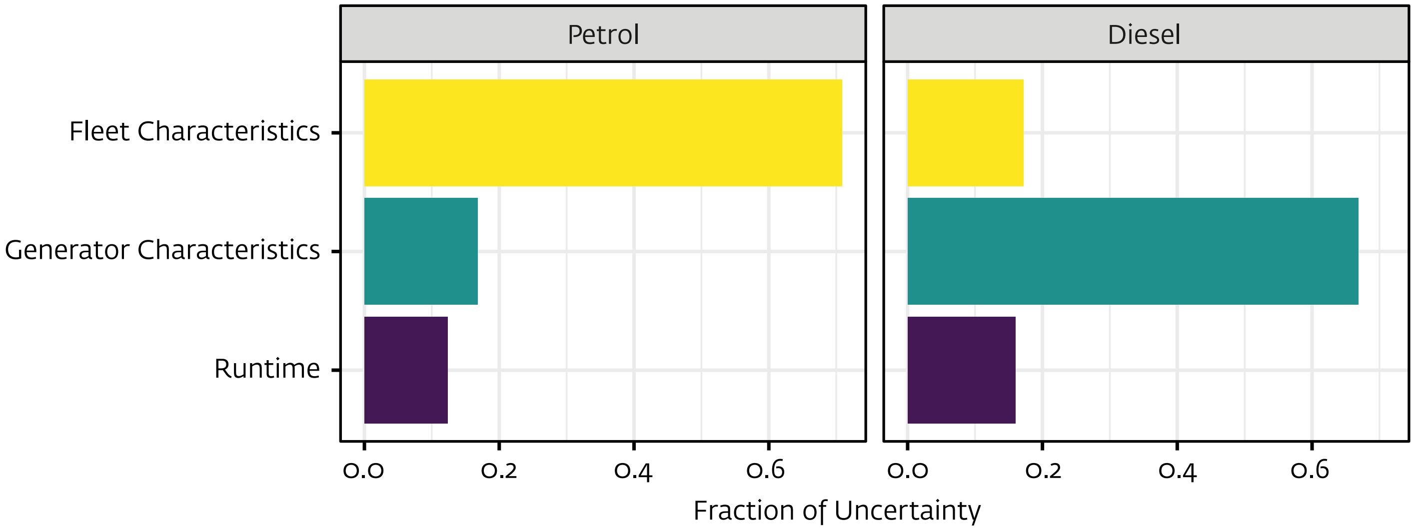
Sources of uncertainty arising from various model inputs were grouped into three knowledge categories:

1. **Fleet Size Characteristics:** Assumptions affecting the size of fleets
2. **Generator Characteristics:** Assumptions affecting the size, performance, and operation of generators in the fleet.
3. **Runtime Characteristics:** Assumptions affecting the utilization rate of generators in the fleet.

Figure 7.1 shows the portion of diesel and gasoline consumption uncertainty attributed to each knowledge category. For gasoline, factors affecting Fleet Size dominate, largely as a result of discrepancies between trade records and survey-based measures of fleet size in the residential and commercial sectors. Uncertainty in diesel consumption is dominated by Generator Characteristics, particularly factors influencing how units in the largest (> 300 kW) size category are operated. Although these units account for a small fraction of units in the fleet (by number), they have the potential to account for a large fraction of generation and consume large quantities of fuel in a short period of runtime. Gasoline generators have maximum output capacities that are roughly 100 times less than the largest diesel generator classes, making Generator Characteristic less influential on total gasoline consumption estimates.

Efforts that address key knowledge gaps in several regions can provide large reductions to overall uncertainty of fuel consumption estimates in developing regions of the world. The large gasoline generator fleets in Western Africa account for most of the total uncertainty in gasoline consumption in this region (**Figure 7.2**). For diesel, Southern Asia dominates, followed by Western Africa. Notability, the relative importance of addressing specific knowledge categories for improving diesel consumption estimates changes by region, suggesting that there may be value in tailoring monitoring strategies accordingly.

FIGURE 7.1: CONTRIBUTION TO UNCERTAINTY IN TOTAL DIESEL AND GASOLINE CONSUMPTION ESTIMATES FOR ALL MODELED COUNTRIES BY KNOWLEDGE CATEGORY



Conversely, the relative importance of knowledge categories in contributing to gasoline uncertainty remain relatively similar across regions, suggesting that a single strategy may be adequate, at least at the regional scale.

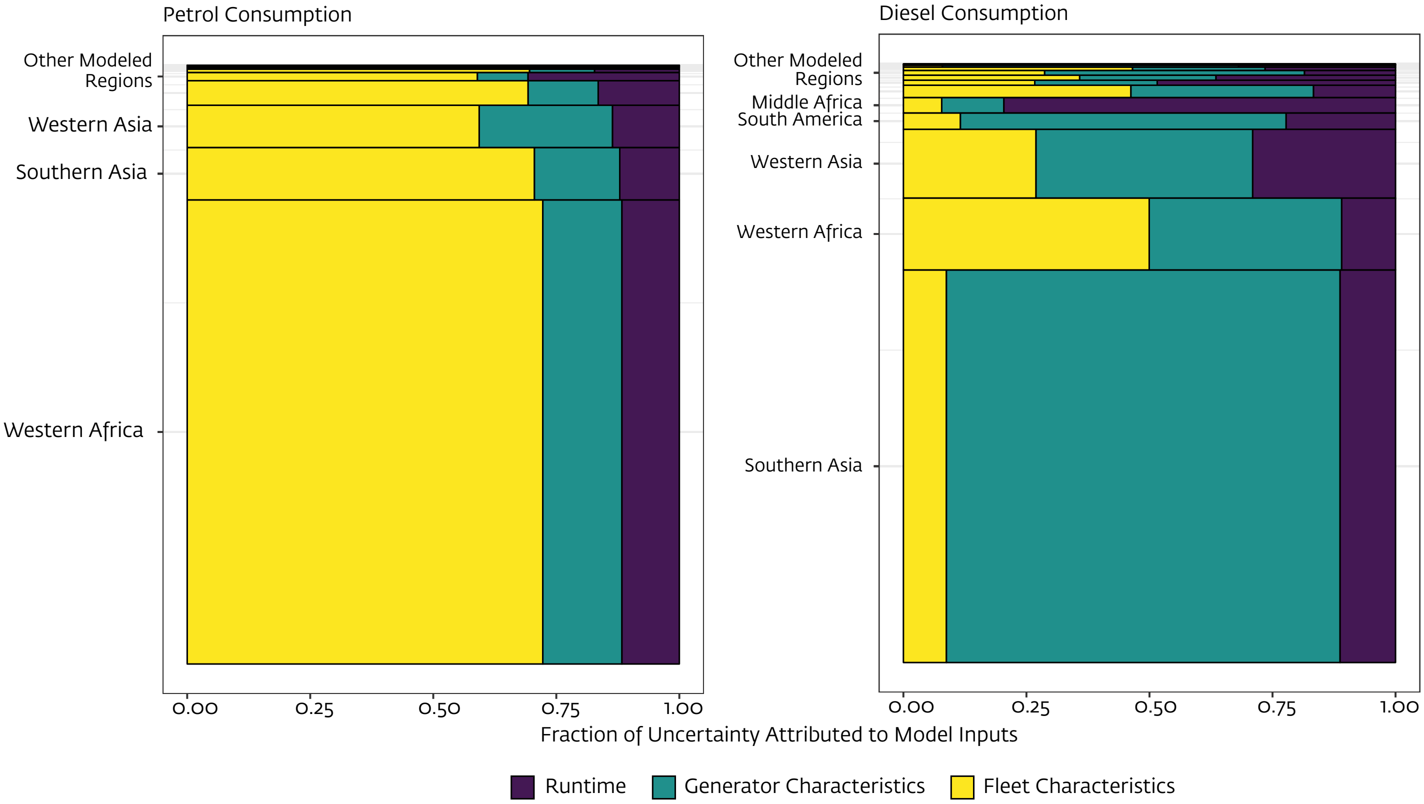
Addressing areas contributing to the uncertainty in diesel consumption appears most important for developing countries given that it accounts for the majority of fuel consumed in most regions for backup generation. Our results reveal, however, that small gasoline generators remain important, accounting for a meaningful fraction of total fossil fuel demand for backup power, and are dominant in some countries, notably Nigeria. How these generator classes reflect distinctions between user segments is also important; for example, an emphasis on gasoline generators and small diesel will likely target domestic and small business users, while larger diesel categories are likely to emphasize commercial and industrial applications. Policy mechanisms and control strategies for affecting change may also vary by sector and user segment, justifying a more granular analysis.

Model assumptions affecting generator Runtime Characteristics had similar importance for gasoline and diesel, accounting for 12 percent and 16 percent of the uncertainty in total fuel consumption, respectively. Although Runtime is identified as lowest priority in terms of improving the precision of our model results, 12 to 16 percent of the total model uncertainty is still large, and improving estimates of SAIDI (the number of hours of power outages) and its relationship with BUGS utilization for various user groups would not only improve accuracy, but would also provide critical knowledge for understanding the viability of generator alternatives. Despite the negative impacts that unreliable electricity supply has on populations and economies, there remains limited data on global power systems, the operational runtimes of generators, and significant discrepancies in coverage and reporting, making comparison across what few data sets exist difficult.[66]

There are some areas of impact that we report on for which our treatment of uncertainty was not applied but are still important for establishing baseline impacts and mitigation potential.

Wherever possible, we applied consistent estimation procedures across all countries examined as part of our study. For some countries, particularly those that manufacture or export large numbers of BUGS, an alternative approach was needed. In India, for example, a bottom-up (sector-by-sector) estimation approach was performed that did not rely on global trade data. More detailed approaches were not possible for all countries for which a standardized approach was deemed inappropriate, however. China and Namibia for example, were excluded from our analysis but are likely important for generator markets and possibly impacts.

FIGURE 7.2: FRACTION OF UNCERTAINTY IN TOTAL GASOLINE (LEFT) AND DIESEL CONSUMPTION (RIGHT) ESTIMATES, APPORTIONED BY REGIONS AND KNOWLEDGE CATEGORY



Another potentially important area not explicitly examined in our uncertainty analysis were gaps in the understanding of emission characteristics of generators. There is extremely limited data on the emissions from generators used in developing countries under typical operation. In the absence of these data, we relied on emission characteristics of new generators, based primarily on laboratory measurements conducted in industrialized countries. Such measurements do not reflect the effects of poor maintenance, age, or fuel quality, for example, on the emission strength of generators.

ENDNOTES

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3 Photo Credit: Bhushan Tuladhar, from Diesel Power Generation: Inventories and Black Carbon Emissions in Kathmandu Valley, Nepal.

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11 SE4All. 2017.

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15 Access to Energy Institute (2019) "Solar Killed the Generator Star" (Video Production) https://vimeo.com/341730105.

16 http://se4all.ecreee.org/sites/default/files/Nigeria_IP.pdf.

17 The uncertainty of variables used to estimate generator fleet characteristics and impacts are considered in our modeling framework. Each input variable is given a range of possible values The 90 percent uncertainty interval (UI) indicates that 90 percent of model runs fell within the specified interval.

18 Koomey, Jonathan, et al. 2010. "Defining a standard metric for electricity savings." Environmental Research Letters 5.1 (2010): 014017.

19 India, Angola, Indonesia, Argentina, Saudi Arabia, Nigeria, Philippines, Venezuela, Bangladesh, Chile, Algeria, Iraq

20 Among the subset of 111 countries that were modeled and total grid capacity estimates were available (98 percent of the modeled population).

21 Koomey, Jonathan, et al. 2010. "Defining a standard metric for electricity savings." Environmental Research Letters 5.1 (2010): 014017.

22 Estimated from 35 of 48 countries in Sub-Saharan Africa for which data on grid generation was available, adjusted for transmission and distribution losses.

23 Values based on import records and do not account for generators assembled or manufactured in country, or units sold via illegal markets.

24 Values based on fleet size estimates and the average unit prices across generator classes from trade records.

25 IMF. 2019. Global Fossil Fuel Subsidies Remain Large: An Update Based on Country-Level Estimates. https://www.imf.org/en/Publications/WP/Issues/2019/05/02/Global-Fossil-Fuel-Subsidies-Remain-Large-An-Update-Based-on-Country-Level-Estimates-46509

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49 Enterprise Surveys (World Bank), Doing Business Surveys (World Bank).

50 Based on an analysis of business expenditure surveys conducted by IFC in Nigeria in 2018–2019 (unpublished).

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