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Electricity and Firm Productivity: A General-Equilibrium Approach

Abstract

Many policymakers view power outages as a major constraint on firm productivity in developing countries. Yet empirical studies find modest short-run effects of outages on firm performance. This paper builds a dynamic macroeconomic model to study the long-run general-equilibrium effects of power outages on productivity. Outages lower productivity in the model by creating idle resources, depressing the scale of incumbent firms and reducing entry of new firms. Consistent with the empirical literature, the model predicts small short-run effects of eliminating outages. However, the long-run general-equilibrium effects are much larger, supporting the view that eliminating outages is an important development objective.

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1. Introduction

Most firms in the developing world put inadequate electricity supply at or near the top of their list of constraints holding back their productivity (World Bank Group, 2017). Not surprisingly then, improving electricity provision has emerged as a top policy priority for many developing countries to promote economic growth. Yet, most existing empirical studies of the effects of power outages on firm productivity have found fairly modest impacts. For example, Allcott, Collard-Wexler, and O'Connell (2016) estimate that Indian manufacturing firms operate at a mere 1.5 percent lower productive level on average due to the (widespread) electricity outages they face. Similar studies also find that power outages lead to small short-run declines in firm productivity across a broad set of developing countries.[1] More generally, a growing micro literature on the effects on electrification has found negligible short-run economic impacts, at least in rural areas (Dinkelman, 2011; Burlig and Preonas, 2016; Lee, Miguel, and Wolfram, Forthcoming). Given the massive differences in aggregate output per capita across countries (Hall and Jones, 1999; Caselli, 2005), these modest estimated effects of electricity suggest that policymakers could be overemphasizing its importance in their development strategy.

In contrast to the previous work, this paper models and quantifies the *long-run, general equilibrium* effects of electricity on firm and aggregate productivity, which we find are much larger than the effects estimated by the literature thus far. To do so, we build a new dynamic macro model that incorporates several key aspects of how electricity is provided in the developing world, and how firms respond, dynamically, to an unreliable electricity supply. First, electricity is a strong complement to capital in the production function and other inputs cannot be easily be substituted for electricity (Atkeson and Kehoe, 1999; Hassler, Krusell, and Olovsson, 2015; Casey, 2018). Second, electricity is provided through the grid at a low price but rationed, with unpredictable power outages occurring in equilibrium (consistent with the evidence of Burgess, Greenstone, Ryan, and Sudarshan, 2020). Third, some firms self-produce electricity using generators, though at a higher cost than electricity purchased from the grid. Fourth, firms can choose not to enter the "modern" electricity-using sector at all, and instead operate a low-productivity "traditional" technology (as in Midrigan and Xu, 2014) that doesn't require electricity. Finally, grid electricity supply endogenously responds to electricity prices, with outages occurring in equilibrium only when prices are held below the market-clearing level.

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[1] Fisher-Vanden, Mansur, and Wang (2015) find a statistically insignificant effect of power outages on firm productivity in a panel of Chinese manufacturing firms. Abeberese, Ackah, and Asuming (2019) and Hardy and McCasland (2019) estimate that outages reduce productivity by 10 to 13 percent for small firms in Ghana, but find no effect on productivity for all other firms. Grainger and Zhang (2017) estimate that outages lead to productivity decreases of less than one percent in Pakistan. Scott, Darko, Lemma, and Rud (2014) find small and generally insignificant correlations between the number of power outages a firm experiences and its labor productivity across a sample of six major developing economies.

To analytically illustrate how power outages affect firm productivity, we first present a simple version of the model in which the probability of a power outage is exogenous. Power outages are unpredictable in the sense that firms know the probability that the power will be on, but they do not know *when* it will be on. These unpredictable outages create idle resources in equilibrium. When the power is off, modern firms idle productive capital if they do not have enough generator capital. When the power is on, modern firms instead idle their generator capital, because the marginal cost of self-generated electricity is higher than the price of grid electricity. We measure the short-run partial-equilibrium effect of eliminating power outages by simulating a counterfactual scenario under which firms make entry and scale decisions assuming that the probability of grid power is less than one, but then experience no outages ex-post. This exercise captures the spirit of the empirical literature described above which focuses on *ceteris paribus* regression counterfactuals, assuming that firms face no power outages, but that all else is constant. We show that eliminating outages increases output per worker in the short-run partial equilibrium only because productive capital is no longer idled.

By contrast, we simulate the long-run general-equilibrium effect of eliminating outages by solving for a new steady state of the model in which firms get grid electricity with probability one. The long-run general-equilibrium effect includes the increases in output per worker from not idling productive capital, as in the short-run partial-equilibrium, plus two additional channels. First, the incumbent modern firms, who now expect never to idle capital in an outage again, demand more productive capital and zero generator capital. Since in steady state, the rental rate on capital is pinned down entirely by the household Euler equation, capital supply, rather than the price of capital, expands to meet the new demand from firms. Second, when there are no outages, more firms produce with the modern technology, which is more attractive now that grid electricity is reliably available.

To quantify the importance of eliminating power outages on firm and aggregate productivity, we extend the simple model to a richer quantitative version which endogenizes the probability of a power outage through a distorted electricity-production sector. We set the electricity price below its market-clearing value, as in the evidence of Burgess et al. (2020), which leads electricity producers to restrict supply. Thus, instead of the price clearing the electricity market, the extent of power outages is determined so that the rationed supply of grid electricity equals the demand at the regulated price. We calibrate the model to match the main features of electricity use in four large Sub-Saharan African countries. The key targets to inform our quantitative analysis are: the importance of electricity in production, the cost of generator electricity versus grid electricity, and the overall prevalence of self-generated electricity. Consistent with the empirical evidence, our calibrated model endogenously predicts a positive correlation between generator ownership and firm size.

We use the calibrated model to simulate the long-run general-equilibrium effects of eliminating power outages on the macroeconomy. In each country, we compare outcomes in an undistorted steady state with no power outages to their values in the initial calibrated steady state, which has widespread outages. To compute the undistorted steady state, we remove the electricity price regulations and allow the price to adjust freely to clear the electricity market. Our model predicts that the short-run partial-equilibrium effects are modest, on the order of a 5 percentage points. These small effects mirror the estimates from the microeconomic literature on electricity and firm productivity, lending credence to the model's short-run partial-equilibrium predictions. In contrast, the long-run general-equilibrium effects of eliminating power outages are three times larger, averaging 15 percent across our countries.[2] Through the lens of development accounting, eliminating power outages works through both higher aggregate capital per worker and higher measured TFP, as fewer resources are idled and production moves into the modern sector.

Importantly, we find that outages more severely constrain economic output than the general electricity-market distortions analyzed by most studies, such a tax on electricity producers or low productivity. In a competitive economy, if output in a particular sector is sufficiently scarce, due to a tax or low productivity, then its price will rise to attract more inputs, thus raising output in that sector. For example, Jones (2011) uses this intuition to illustrate that low-productivity (weak-link) sectors do not reduce aggregate output as much as one might expect. However, these competitive forces are not active in our setting because the regulated electricity price prevents resources from reallocating to the electricity sector. Consequently, outages can lead to much larger reductions in aggregate output.

We conclude by providing new evidence that helps validate the model's long-run aggregate predictions, which are harder to test in practice. We conduct new surveys of firms in Nigeria and Ghana about the expected effects of permanently eliminating power outages. The majority of Ghanaian and Nigerian firms report that eliminating outages would be likely or very likely to expand their own investment and hiring, consistent with the model's firm-expansion channel. An even larger fraction of firms in both countries expect that permanently eliminating outages would lead to entry of new firms into their industry, just as the model's firm-entry channel predicts. As a frame of reference, we also surveyed firms from the same population about the

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[2] These larger longer-run effects are similar in spirit to the literature on the long-run regional effects of electricity (Rud, 2012; Lipscomb, Mobarak, and Barham, 2013), who find large long-run differences in economic development across regions within countries with differing levels of electrification. Rud (2012) studies a panel of Indian states between 1965 and 1984, while Lipscomb et al. (2013) consider a panel of Brazilian states from 1960 to 2000.

likely effects of a placebo "treatment" in which the national airports convert to solar power, on the exact same outcomes. Across both countries and all questions, the expected effects of eliminating power outages are economically and statistically larger than the effects of the placebo, suggesting that our results are unlikely to be artifacts of misreporting by survey respondents.

Our paper builds on two distinct literatures in macroeconomics. The first is the growing macro development literature that draws on dynamic general equilibrium models to understand how the partial equilibrium effects of development policies– informed by reduced-form empirical evidence– compare to the long-run general equilibrium effects. Our quantitative exercises are particularly related to those of Buera, Kaboski, and Shin (2019), who use a macroeconomic model of credit constrained firms to infer how the general equilibrium effects of microfinance lending differ from the partial equilibrium effects estimated in the empirical literature on micro finance. Also in this vein, Brooks and Donovan (2020) flush out the general-equilibrium effects of improved transportation infrastructure on rural farmers starting with reduced-form evidence on the effects of rural bridge building. Using a similar methodology, Lagakos, Mobarak, and Waugh (2020) quantify the aggregate effects of subsides to rural-urban migration, and Akcigit, Alp, and Peters (2021) infer the general equilibrium effects of improving managerial capabilities.

The second literature on which we build is the recent literature on sector linkages and development, which studies how low productivity in one intermediate sector – especially one that exhibits a high degree of complementarity with other sectors– can have a disproportionate effect on aggregate output per worker (Bartelme and Gorodnichenko, 2015; Baqaee and Farhi, 2019).[3] Electricity is a classic example of such an input, and our paper is the first to study the general equilibrium implications of distortions in the electricity sector. Boehm and Oberfield (2018) focus on a different type of distortion stemming from a government inability to enforce contracts between firms, and study how that propagates through linked sectors. Liu (2019) builds a model in which distortions at the sector level accumulate through backward demand linkages. The most upstream sectors become the "sink" for market imperfections, which may well apply to electricity production, though this channel is not present in the current model. Baqaee and Farhi (2020) show that sectoral shocks in a distorted economy, such as ours, can be far more potent than in an efficient one, since moving resources out of a distorted sector can have first-order effects on output.

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[3] Most of this literature has focused on business cycle fluctuations, rather than long-run outcomes, and has largely concluded that input-output linkages play an important role in amplifying short-run microeconomic shocks; see Carvalho (2014) for an insightful overview of the literature. Empirically, di Giovanni, Levchenko, and Méjean (2014) draw on rich firm-level data to document that firm-specific shocks contribute to aggregate fluctuations mainly through firm-to-firm linkages. Similarly, Atalay (2017) shows that outputs at the sector level are strong complements, implying that shocks to individual sectors have out sized aggregate impacts.

2. Electricity and Firms in the Developing World: Stylized Facts

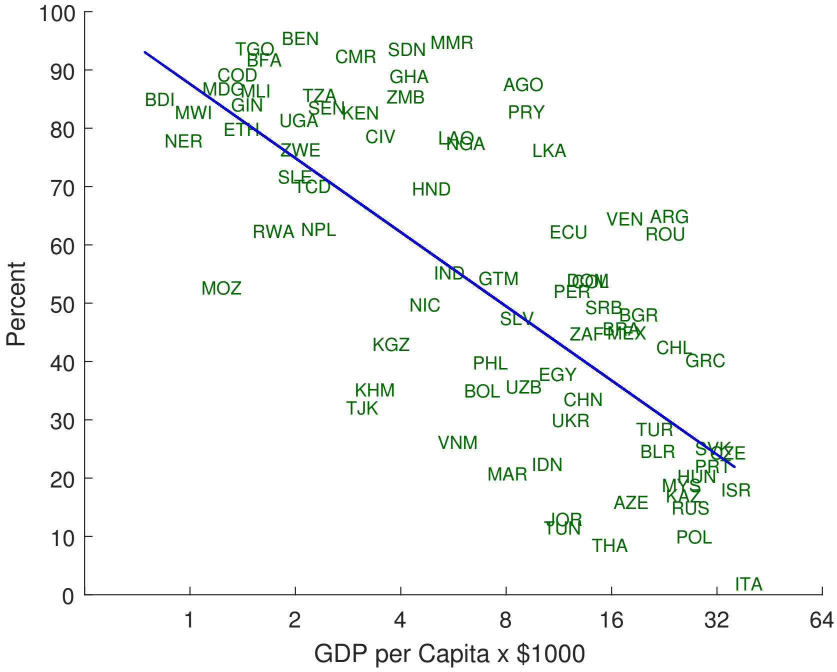
To motivate our model of electricity and firm productivity, we begin by summarizing four key facts about electricity in developing countries. To be sure, these facts are known by those who study electricity in developing countries, though they are likely to be less well known by macroeconomists. First, grid electricity is rationed to firms through frequent and unpredictable power outages. Second, some firms use generators to produce their own electricity to insure themselves against grid electricity shortages. Third, the cost to firms of self-generated electricity is substantially higher than the cost of grid electricity. Fourth, the electricity sector itself is highly distorted, with prices held at below-market levels in most countries.

Firms experience frequent unpredictable power outages. Unlike in advanced economies, the electricity grid is highly unreliable in developing countries. Even firms with grid connections still experience frequent and unpredictable power outages (see e.g., Eberhard, Rosnes, Shkaratan, and Vennemo 2011; Scott et al. 2014). To illustrate how frequent power outages are in the developing world, we draw on evidence from the World Bank's World Enterprise Surveys (WES), which cover random samples of medium and large firms from a large set of countries (though the richest countries are excluded).

Figure 1 plots the percent of firms in the WES that report having experienced an electricity outage in the last month against GDP per capita. Each point on the graph represents the averages for all firms sampled in the WES by country in the most recent available year. The figure presents a very stark picture of how common electricity outages are in the developing world. In most of the word's poorest countries, more than eight out of ten firms experienced an outage in the last month. Across all countries in the data, the average percent of firms experiencing outages is 55 percent. There is also a clear negative relationship with outages and GDP per capita; nearly all the firms in the poorest countries experienced outages in the last month, but only one quarter of the firms experienced outages in the WES countries with the highest GDP per capita. The world's richest countries are not covered by the WES, but it is well-known that outages there are extremely infrequent. Power outages are, in other words, almost a defining feature of developing economies.

Some firms self-generate electricity to insure against outages. Since electricity outages are clearly undesirable for firms, many of them self-produce electricity using generators (Alby, Dethier, and Straub 2013; Eberhard et al. 2011; Foster and Steinbuks 2008). The ability to self-produce electricity allows firms access to electricity during an outage, which must be valuable given the frequency of outages. To see how much self-generation goes on in practice in the developing world, we turn again to the WES, at least for evidence on self-generation among

Figure 1: Percent of Firms Experiencing Electricity Outages



Note: This figure plots the percent of firms in the World Bank's World Enterprise Surveys that experienced an electricity outage in the last month against 2013 GDP per capita. The figure includes all countries with a population greater than five million and a survey covering at least one hundred firms.

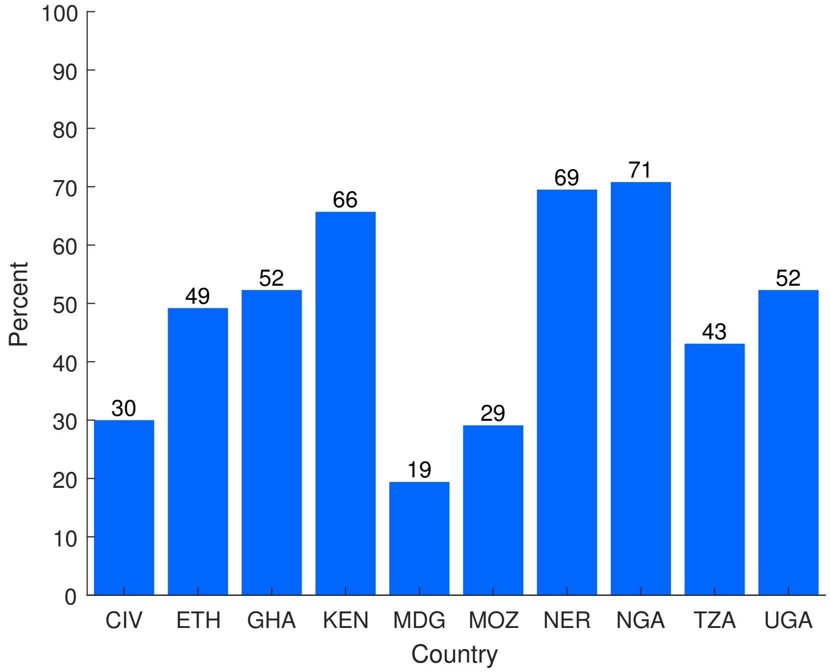
the relatively large firms that make up the WES sample. We focus on a set of ten large African countries for which we have comparable data on other dimensions, which we discuss below.

Figure 2 plots the percent of firms in the WES that own or share a generator at the time of the survey in these ten countries. The generator ownership rate is 48 percent on average across these countries. Nigeria, which is Africa's largest economy, has the highest generator ownership rate, at 71 percent. Madagascar has the lowest rate at 19 percent. When looking across all countries in the WES, there is a strong negative correlation between generator ownership and GDP per capita, with less than 10 percent of firms in the richest WES countries owning generators. Thus, it is clear that many firms in the developing world use generators to insure themselves against outages, though far from all firms have access to generators.

Self-generated electricity is more expensive than grid electricity. Even though firms can produce their own electricity, this does not mean that firms are indifferent between getting their electricity from the grid or producing it themselves using generators. Evidence shows that self-generated electricity is substantially more costly for firms than grid electricity (Foster and Steinbuks, 2008).

Figure 3 plots estimates of the average cost of grid electricity and self-generated electricity in

Figure 2: Percent of Firms Owning or Sharing a Generator



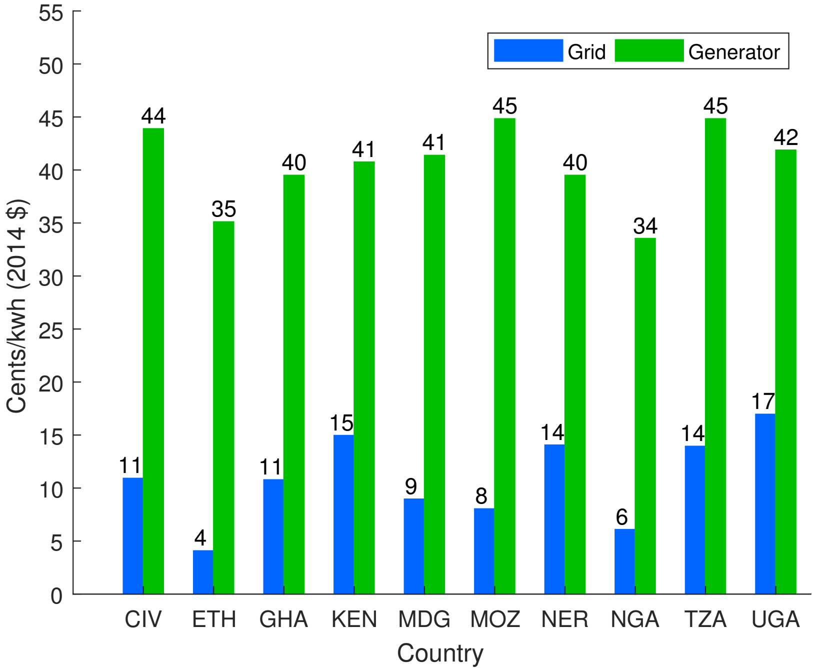
Note: This figure plots the percent of firms that own or share a generator in the ten most populous countries in Sub-Saharan Africa that have the data required for both Figures 2 and 3. The data on generator access are from the World Bank's World Enterprise Surveys.

the ten largest Sub-Saharan African countries for which data are available. The average cost of self-generated electricity includes the capital costs of owning a generator, based on estimates in World Bank (2007), plus the cost of fuel for the generator (see Appendix C for details on these calculations).

The average cost of self-generated electricity ranges from a low of $0.34 per kWh in Ethiopia to a high of $0.45 per kWh in Mozambique (reflecting differences in the price of fuel). Grid electricity prices range from $0.04 per kWh in Ethiopia to $0.17 per kWh in Uganda (Trimble, Kojima, Arroyo, and Mohammadzadeh, 2016). The variation in the grid electricity price likely reflects differences in official tariffs as well as differences in bill collection rates and theft. On average, self-generated electricity is approximately four times as expensive as grid electricity.

Importantly, the high average cost of self-generated electricity results from both the high cost of the generator equipment and the high cost of the fuel necessary to run it. The marginal cost of self-generated electricity, which depends on the price of diesel fuel and the efficiency of the generator, is on average three times higher than the price of grid electricity. Thus, while firms with generators do have the ability to produce their own power during an outage, the cost of their electricity inputs are substantially higher when they self-produce, than when they

Figure 3: Average Cost of Electricity: Grid vs. Generator



Note: This figure plots the effective price of grid electricity and the average cost of self-generated electricity in the ten most populous countries in Sub-Saharan Africa for which data are available. Data on the effective price of grid electricity, accounting for theft and lapses in bill collection, are from Trimble et al. (2016). We calculate the average cost of generator electricity from estimates of the capital cost of a typical diesel generator from World Bank (2007) and the price of diesel fuel. See Appendix C for a full description.

directly purchase electricity from the grid.

Grid electricity provision is highly distorted. It is well known that the public sector regulates electricity providers in most countries. The developing world provides few exceptions to this rule. Moreover, as Trimble et al. (2016) document, virtually none of the electricity sectors in Sub-Saharan Africa collect enough revenue to recover their costs. One reason for this is the low official tariffs for electricity. Burgess et al. (2020) argue that governments in developing countries present electricity as a basic right for their citizens, and, as a result, political incentives play a substantial role in keeping electricity prices regulated at levels that are unprofitable for power producers.

A second, related, reason that electricity prices are so low is the rampant non-payment that prevails throughout the developing world (see Jack and Smith, 2015). As Burgess et al. (2020) colorfully illustrate, power producers in the power sectors of Bihar, India have an official rate of $0.10 per kWh, which should, in principle, be enough to cover their production cost of about $0.06 per kWh. Yet power producers collect only around $0.01 per kWh after subsidies, technical losses, un-billed power and unpaid bills are taken into consideration! While the numbers differ in Africa, the problems are largely similar: technical losses, un-billed power and underpayment all cut into the effective prices of grid electricity (Eberhard et al. 2011; Jack and Smith 2015; Dzansi, Puller, Street, and Yebuah-Dwamena 2018).

In sum, the price of grid electricity is regulated to be too low across the developing world, and this regulation is the proximate cause of the widespread power outages there (Burgess et al., 2020; Eberhard et al., 2011). Some firms can insure against these outages by producing their own electricity with generators. However, the self-generation of electricity is expensive because both the average and marginal cost of self-generated electricity are considerably higher than the effective price of grid electricity.

3. Simple Model of Electricity and Firm Productivity

We now build a simple, dynamic, general-equilibrium model that incorporates the key features of electricity supply in developing countries presented in the previous section. The model is intentionally stylized to provide an analytic characterization of how power outages impact firm productivity in general equilibrium. In particular, the model takes the probability of grid power as exogenous, abstracts from hired labor input, sets the price of grid electricity to zero, and assumes that an exogenous fraction of modern firms have the option to purchase generators. We relax all of these assumptions in Section 4 to follow. We relegate all proofs and the definition of an equilibrium to Appendix A.

Environment. The economy is inhabited by a representative household that chooses consumption and saving each period to maximize, $\sum_{t=0}^{\infty}\beta^t u(C_t)$, where $\beta \in (0,1)$ is the discount factor, C_t is consumption, and $u(\cdot)$ is a concave, strictly increasing and continuously differentiable period utility function. Households save in physical capital. Capital accumulates according to the law of motion, $K_{t+1} = (1-\delta)K_t + I_t$, where $\delta \in [0,1]$ is the depreciation rate and I_t is the number of final goods saved as investment. Households rent capital to firms at rate R_t. Household income includes the payments to capital and profits from the firms (described below).

There is a unit measure of heterogeneous entrepreneurs that operate firms and produce a homogeneous final good using their managerial ability and capital input. Each entrepreneur draws her managerial ability, z, from distribution $G(z)$ with support $z \in [1,\infty]$. Entrepreneurs can choose to operate either in the "traditional sector" or in the "modern sector". The sectors differ in terms of their production technologies and associated input requirements. If the entrepreneur chooses to operate in the modern sector, she must pay an entry cost, Ω.

The production function in the traditional sector is:

$$y_t^T = z^{1-\eta}[k_t^T]^{\eta}, \tag{1}$$

where y_t^T is output of the final good, k_t^T is the capital input and $\eta \in [0,1]$ measures the entrepreneur's span of control. The traditional entrepreneur chooses capital to maximize profits, π^T, where profits are the difference between production and rental payments for capital.

The production technology in the modern sector differs from that of the traditional sector in two ways. First, it uses managerial and capital inputs more efficiently. Second, it requires electricity. As discussed in Section 2, the supply of grid electricity is rationed and unpredictable, meaning frequent power outages. To incorporate this unpredictable rationing into the model, we divide the time period into a continuum of measure one of "instants." We model the availability of grid power in each instant i of period t as the realization of an exogenous random variable: with probability v, grid power is available in instant i and with probability $1-v$, grid power is not available. As such, v corresponds to the fraction of the period that the power is on and $1-v$ corresponds to the fraction of the period that the power is off. While the firms know the value of v, they do not know when during the period the power will be on or off, implying that they cannot schedule production to occur only during the instants when the power is on.

Following Hassler et al. (2015), the modern firm's output in each instant i, y_{it}^M, is a Leontief function between capital and electricity:

$$y_{it}^M = A^M z^{1-\eta}\left[\min(k_t^M, e_{it})\right]^\eta, \tag{2}$$

where e_{it} is the electricity that the firm uses during instant i to operate her capital input, and A^M is the TFP in the modern sector. We require that $A^M > \left[(1-\gamma)v^{1/(1-\eta)}\right]^{-1/(1-\eta)}$, which ensures that entrepreneurs operate in both sectors in equilibrium. When capital and electricity inputs are equated, the production function equals $A^M z^{1-\eta}[k_t^M]^\eta$, mirroring the production function in the traditional sector, but with higher productivity.

All instants when grid power is on are symmetric and all instants when grid power is off are symmetric. Let y_{1t}^M denote output during any instant when the power is on and y_{0t}^M denote output during any instant when the power is off. The firm's total output in period t, y_t^M, equals the sum of output during the instants when grid power is on and output during the instants when grid power is off:

$$y_t^M = v y_{1t}^M + (1-v) y_{0t}^M. \tag{3}$$

There are two ways a modern firm can acquire electricity in each instant. First, if available, it can get it from the electricity grid, e_{it}^G, at a "below-market" price that we set to zero for simplicity. Second, a fraction of modern firms can produce their own electricity, e_{it}^S, at a higher cost. As discussed in Section 2, many, but not all, modern firms in low-income economies have access to generators. Some modern firms might not have generators because of financing constraints, the absence of markets for generators, poor distribution networks for diesel fuel, or lack of parts or repair facilities (Scott et al., 2014). To capture this stylized fact while keeping the analytic model as simple as possible, we assume that a fraction γ of modern firms have access to generators and a fraction $1-\gamma$ do not. An entrepreneur learns if she has generator access after she enters the modern sector. Even though generator access grants the firm the ability to rent a generator and produce its own electricity, it does not require the firm to do so. Firms with generator access endogenously decide how much electricity to self-produce, if any.

After they are produced, grid and self-generated electricity are perfect substitutes in the production of the final good. For example, if a machine requires five kilowatt-hours of electricity to operate, it does not matter if those kilowatt-hours are produced by a diesel generator or by a coal-fired power plant. To generate its own electricity in instant i, the firm combines self-generation capital, k_t^S, with fuel, f_{it} (denominated in units of final good), according to:

$$e_{it}^S = \min[k_t^S, f_{it}]. \tag{4}$$

The marginal cost of a unit of grid electricity is one unit of the final good, which is used as fuel for the generator. Since all instants without power are symmetric, we use the notation f_{0t} to denote the firm's demand for fuel during any instant without power.

Power outages in the model correspond to instants when the power is off and the firm produces y_{0t}. The direct effect of these outages for firms with generators is that they must self-produce all of their electricity inputs. If they do not have enough generator capital to operate their productive capital at full capacity, then they must idle some productive capital, partially halting production. The direct effect of outages for firms without generators is to halt all production. In practice, power outages often require halting production because they lead to assembly line disruptions, failure of electrically operated machines, and loss of lighting (Scott et al., 2014).

Modern firm's problem. We first describe the optimization problem for modern firms with generator access. At the start of period t, each modern firm chooses its capital input, k_t^M, and generator capital, k_t^S, both of which are then fixed for the entire period. During each instant, the firm chooses its electricity input. If the grid power is on, the firm gets electricity from the grid (since it has zero marginal cost). If the grid power is off, the firm either produces its own electricity or simply idles its capital input. The firm's profits are the difference between production and the costs of generator capital, productive capital and fuel:

$$\pi_t^M = \nu y_{1t}^M + (1-\nu)\big(y_{0t}^M - f_{0t}\big) - R_t(k_t^S + k_t^M). \tag{5}$$

Importantly, the firm only pays for fuel during instants when the power is off. In contrast, the firm must rent the generator and productive capital for the entire period. Since power outages are unpredictable, as discussed in Section 2, firms cannot rent a generator only when the power is off, or productive capital only when the power is on.

Profit maximization in the presence of power outages presents firms with a dismal trade-off. A firm can purchase enough generator capital to operate its productive capital at full capacity when the power is off. But then it must idle generator capital when the power is on. Alternatively, the firm can purchase less generator capital, and thus reduce its idle generator capital when the power is on. But then it must idle some productive capital when the power is off.

Formally, the modern firm's problem is to choose k_t^M, k_t^S, e_{1t}^G, and f_{0t} to maximize profits, taking the probability of grid power, ν, and the rental rate of capital, R_t, as given. The Lagrangian for the firm's problem can be written as:

$$\mathcal{L} = \nu A^M z^{1-\eta}(k_t^M)^\eta + (1-\nu)\big(A^M z^{1-\eta}(k_t^S)^\eta - k_t^S\big) - R_t(k_t^S + k_t^M) + \theta\left(k_t^M - k_t^S\right), \tag{6}$$

where θ represents the Lagrange multiplier on the inequality constraint that $k_t^S \leq k_t^M$. This inequality constraint arises from the firm's trade-off between idling productive capital and idling generator capital. It is never optimal to produce more self-generated electricity than is required to operate the productive capital, implying that generator capital will never exceed productive capital, i.e. $k_t^S \leq k_t^M$. Yet, it could be optimal to hold *less* generator capital than is necessary to operate the productive capital at full capacity when the power is off, i.e. $k_t^S < k_t^M$.[4]

The optimization problem for modern firms without generator access is similar to the above discussion except that generator capital always equals zero. Hence, the firm must idle all of its productive capital input during an outage, implying that its profits equal equation (5) with the self-generation terms set to zero: $y_{0t} = f_{0t} = k_t^S = 0$.

We now characterize how the availability of grid power, ν, affects modern firms' optimal levels of productive capital and of generator capital (for those firms with generator access).

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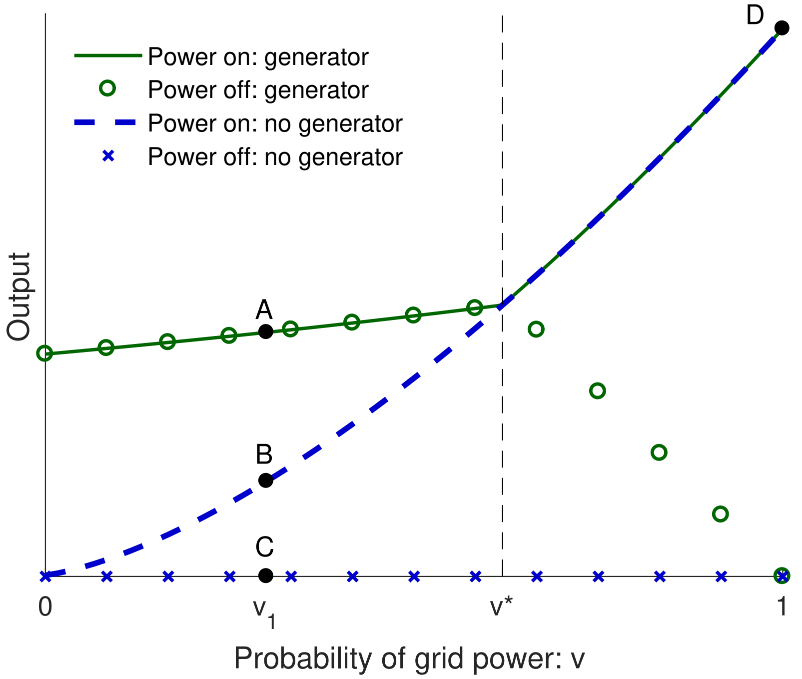
[4] By contrast, the other Leontief production functions – (2) when the power is on, and (4) when the power is off – both hold with equality. That is, $f_{0t} = k_t^S$, since it is never optimal to purchase more or less fuel than is necessary to operate the generator capital at full capacity when the power is out, and $e_{0t}^G = k_t^M$, since it is never optimal to use more or less grid electricity than is necessary to operate the productive capital when the power is on.

Figure 4: Solution to the Modern Firm's Problem



Note: The green solid line and o's plot production by a modern firm with generator access when the power is on and off, respectively. The blue dashed line and x's plot production by a modern firm without generator access when the power is on and off, respectively. Value $v^\star$ corresponds to the cutoff from Proposition 1.

Proposition 1. *The firm's productive capital input is increasing in the probability of grid electricity, v, for any R_t. Firms with generator access idle generator capital when the power is on for any $v < 1$. For these firms, there exists a cutoff $v^*(R_t) \in (0,1)$ such that when $v < v^*(R_t)$, generator capital is increasing in v and no productive capital is idled. When $v \geq v^*(R_t)$, generator capital is decreasing in v and productive capital is idled when the power is off. Generator capital equals zero when $v = 1$.*

Figure 4 illustrates the implications of Proposition 1 for optimal production by modern firms with a given productivity, z. The green solid line and the green o's plot production by modern firms with generator access during instants when the power is on and off, respectively. Similarly, the blue dashed line and the blue x's plot production by modern firms without generator access during instants when the power is on and off. Moving from left to right on the x-axis increases the probability of grid power from zero (no grid power) to one (no outages). The value $v^\star$ corresponds to the threshold in Proposition 1, beyond which firms with generators choose to idle some productive capital during an outage.

We focus first on the production decisions by the firms with generator access (green solid line and o's). When $v < v^\star$, firms operate their productive capital at full capacity when the power is off, implying that output is the same during instants with and without grid power. When $\nu > \nu^\star$, firms idle some of their productive capital when the power is off. As a result, output is lower when the power is off than when the power is on. When $\nu > \nu^\star$, output when the power is off decreases with ν because firms rent less generator capital as the probability of grid power increases. The intuition is that when ν is high, outages are sufficiently rare such that it is optimal for firms to idle some of their productive capital during the occasional outage.

We turn next to the firms without generator access. Regardless of the probability of grid power, these firms cannot produce when the power is off, hence the blue x's always equal zero. When the power is on and $\nu < \nu^\star$, output produced by firms without generator access is less than output produced by firms with generator access (e.g. the dashed blue line is below the solid green line). The marginal product of productive capital is lower for firms without generator access because they must idle this capital for fraction $1-\nu$ of the period. As a result, they rent less productive capital and thus produce less output when the power is on. In contrast, when $\nu \geq \nu^\star$, output produced by firms with and without generator access is equal during instants with grid power. In this region, the marginal product of productive capital is the same for firms with and without generator access because both types of firms idle the marginal unit of productive capital when the power is off.

Importantly, output when the power is on increases with the probability of grid power for all modern firms (e.g., the solid green and dashed blue lines are upward sloping). The reason is that increases in the probability of grid power increase the marginal product of productive capital because it is idled for a smaller fraction of the period (for modern firms without generators, and for all modern firms when $\nu > \nu^\star$) and because having access to grid power for a longer fraction of the period reduces the average cost of electricity over the period (for modern firms with generators). As a result, all modern firms scale up production by renting more productive capital.

We define the *short-run partial-equilibrium effect of eliminating outages* as the increase in the firm's output when it learns that there will be no outages ex-post, after it has already made its long-term input decisions. This definition captures the spirit of the microeconomic literature on power outages and firm productivity which considers the effect of eliminating outages on firms who have already made their entry and scale decisions. We can use Figure 4 to understand the short-run partial-equilibrium effects of eliminating outages in the context of our model. For example, consider an economy with probability of grid power ν_1. The short-run partial-equilibrium effect of eliminating outages for firms without generator access is the increase in output when they produce at point B for the entire period, instead of switching between points B and C. The short-run partial-equilibrium effect of eliminating outages for firms with generator access is zero because they produce at point A for the entire period, regardless of whether the power is on or off. Hence, all of the short-run partial-equilibrium gains in output per worker arise because firms without generator access no longer idle productive capital. However, eliminating outages in the short-run partial-equilibrium does not remove idle resources from the economy altogether because firms with generator access still rent generators, which they now idle for the entire period.

In addition to firms' short-run partial-equilibrium response to outages, Proposition 1 implies that eliminating outages causes existing modern firms to demand more productive capital and zero generator capital, all else constant. This increase in scale implies that not only do the firms produce on the power-on line for the entire period, but they also incorporate that $\nu = 1$ into their optimal production decisions by moving all the way to the right along the x-axis in Figure 1. Consequently, eliminating outages (holding fixed R_t) increases output produced by modern firms with and without generator access to point D in the upper-right corner of Figure 4. Like the short-run partial-equilibrium effect, firms do not idle productive capital at point D because the power is on for the entire period. But unlike the short-run partial-equilibrium effect, firms also do not idle generator capital at point D because they know ex-ante that there will be no outages, and hence they do not rent any generator capital to begin with.

Modern-sector entry. Having characterized the optimal behavior of firms in the modern sector, we now turn to the decision of whether to enter the modern sector. The entrepreneur enters the modern sector if the expected value of profits in the modern sector minus the entry cost exceeds the value of profits in the traditional sector: $E(\pi_t^M) - \Omega \geq \pi_t^T$, where the expectation is taken over whether not the entrepreneur has generator access. We show in Appendix A that as long as there exist entrepreneurs in both sectors, then the difference in expected profits, $E(\pi_t^M) - \pi_t^T$, is increasing in z. Thus all entrepreneurs with $z > z_t^\star$ enter the modern sector, where productivity cutoff $z_t^\star$ is the value of z such that $E(\pi_t^M) - \Omega = \pi_t^T$. This result implies that lower productivity entrepreneurs operate in the traditional sector and higher productivity entrepreneurs operate in the modern sector. Firm size increases with the entrepreneur's productivity, thus the smallest firms are traditional and the largest firms are modern.

Long-run general-equilibrium effects of power outages. We define the *long-run general-equilibrium effect of eliminating outages* as the steady state increase in aggregate output (and other equilibrium variables) when we increase the probability of grid power from its existing value to one. We first characterize how the probability of grid power affects entry into the modern sector in the long-run general equilibrium.

Proposition 2. *The steady-state productivity cutoff, $z^\star$, is decreasing in the probability of grid power, ν.*

Intuitively, an increase in the probability of grid power raises the profitability of the modern sector without impacting the profitability of the traditional sector. Consequently, more entrepreneurs choose to become modern, decreasing the productivity cutoff, $z^\star$.

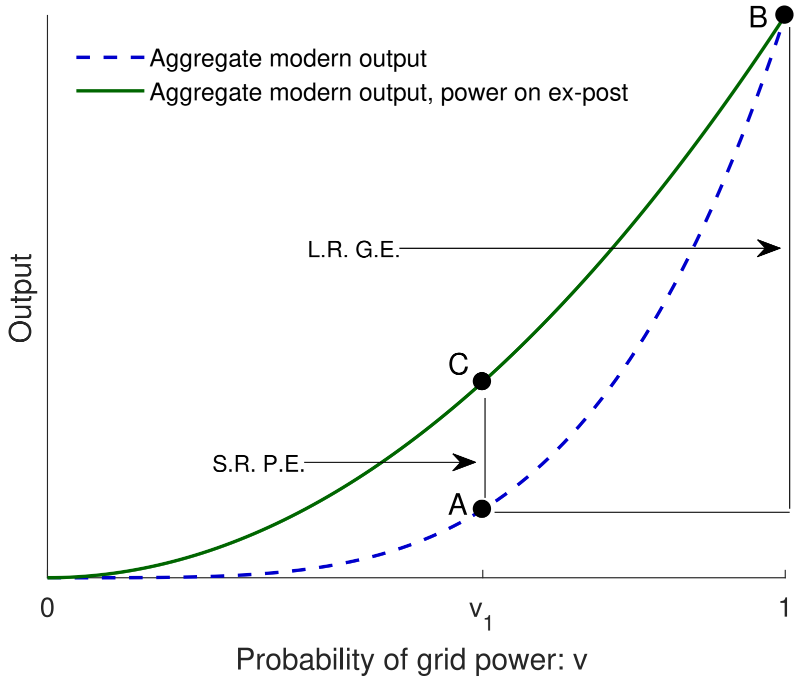
Our analytic model allows us to compare the short-run partial-equilibrium effect of eliminating outages with the long-run general-equilibrium effect. The short-run partial-equilibrium effect corresponds to the increase in aggregate output when power outages are eliminated ex-post. The long-run general-equilibrium effect incorporates the effects of two additional channels. First, since the steady-state rental rate is pinned down by the household Euler equation, Proposition 1 implies that all existing modern firms scale up their production by demanding more productive capital and reducing their demand for generator capital to zero. We call this the *firm-expansion channel*. Second, Proposition 2 implies that more entrepreneurs enter the modern sector, increasing modern output and decreasing traditional output. We call this the *firm-entry channel*. A key difference between the short-run partial-equilibrium and the long-run general-equilibrium effects is that the long-run general-equilibrium effect accounts for the fact that permanently eliminating outages changes firms' expectations and hence their behavior with regards to entry and their scale of operation, represented by their choices of productive and generator capital.

Proposition 3. *For any $v < 1$, the long-run general-equilibrium effect of eliminating outages is larger than the short-run partial-equilibrium effect.*

Figure 5 illustrates the implications of Proposition 3 for aggregate modern output, which is at the heart of the proposition's result. The dashed blue line plots aggregate modern output as a function of the probability of grid power. Increases in the probability of grid power increase aggregate modern output through both the firm-expansion and the firm-entry channels. The solid green line plots aggregate modern output when outages are eliminated after firms have already made their capital and entry decisions.

To compare the short-run partial-equilibrium increase in aggregate modern output with the long-run general-equilibrium increase, consider an economy with probability of grid power, v_1. The short-run partial-equilibrium increase in aggregate modern output from eliminating outages is the increase from point A to point C. Point A corresponds to aggregate modern output when the probability of grid power equals v_1 and firms internalize this probability into their entry and capital decisions. Point C corresponds to aggregate modern output when firms make their entry and capital decisions assuming that the probability of grid power equals v_1, but the actual probability equals 1. Aggregate modern output at point C is higher than at point A because firms produce on their power-on lines in Figure 4 for the entire period.

Figure 5: Short-Run Partial-Equilibrium and Long-Run General-Equilibrium Effects of Outages



Note: The dashed blue line plots aggregate modern-sector output. The solid green line plots aggregate modern output when firms make their entry and scale decisions assuming the probability of grid power equals the value of v on the x-axis but the actual probability equals one. The short-run partial-equilibrium increase in aggregate modern output equals the vertical distance from A to C and the long-run general-equilibrium increase equals the vertical distance from A to B.

The long-run general-equilibrium increase accounts for the effects of the firm-expansion and firm-entry channels by moving all the way to the right on the x-axis, increasing aggregate modern output from point A to point B. Graphically, the increase in aggregate modern output from A to B always exceeds the increase from A to C because the firm-expansion and firm-entry channels imply that both lines must be upward sloping and they must be equal when $v = 1$.

The overall lesson from the model is that looking only at the short-run effect of eliminating outages on firm productivity paints an incomplete picture of the total effect. In the longer run, firms anticipate that there will be no outages. As a result, they demand more productive capital and zero generator capital, scaling up their operations. New firms choose to operate with better, electricity-using, technologies. Combined, these two channels cause output per worker to rise more in the long-run than in the short-run.

4. Quantitative Model

To quantify the long-run general-equilibrium effect of eliminating outages, we extend the model from Section 3 in ways that are useful for the numerical analysis, but leave the fundamental intuition unchanged. Most importantly, we model power outages as the economy's endogenous response to a regulated electricity price that the government fixes below the market-clearing level. As a result, the supply of grid electricity is less than the demand. The amount of rationing, and hence the probability of grid power, is determined so that the rationed demand for grid power equals the amount supplied at the regulated price.

Additionally, the quantitative model endogenizes the extensive margin of generator access and includes hired labor as a production input in the traditional and modern sectors. We assume that a fraction of entrepreneurs never experience outages to capture the possibility that some entrepreneurs have political connections that grant them better access to power. We also add additional parameters in the Leontief production functions to allow them to better match the data and specify the distribution of entrepreneur productivity. We describe the main features of the quantitative model below. We relegate the definition of an equilibrium to Appendix B.

Labor, self-generation, and managerial productivity. The household is endowed with one unit of labor which she supplies inelastically to the labor market. She earns labor income W_t in each period t. Both traditional and modern firms use labor, in addition to capital, in the production process. The traditional and modern production functions for a firm with productivity z are:

$$y_t^T = A^T z^{1-\eta}[(k_t^T)^\alpha (n_t^T)^{1-\alpha}]^\eta \quad \text{and} \quad y_{it}^M = A^M z^{1-\eta}\left[\min((k_t^M)^\alpha (n_t^M)^{1-\alpha}, \mu e_{it})\right]^\eta . \tag{7}$$

Parameter α denotes capital's share in the capital-labor composite and parameter μ controls how much electricity is required to operate the capital-labor composite. Parameter A^T denotes the TFP of the traditional sector. We define parameter $\phi > 1$ to be the TFP boost from the modern production technology: $A^M \equiv \phi A^T$.

The production function for self-generated electricity is:

$$e_{it}^S = A^S \min[k_t^S, \chi f_{it}], \tag{8}$$

where parameter A^S is TFP in the production of self-generated electricity and parameter χ controls how much fuel is required to operate the self-generation capital.

Each entrepreneur draws her level of managerial productivity, z, from the Pareto distribution, $G(z) = 1 - \left(\frac{1}{z}\right)^\lambda$, where $\lambda > 1$ and $z \in [1, \infty]$.

Political connectedness. As Figure 1 highlights, most, but not all firms in developing economies experience outages. It's possible that some entrepreneurs are granted special access to power through their political connections or other mechanisms (Cotton et al., 2019). For example, entrepreneurs could be located in Special Economic Zones which can often have their own high priority transmission lines. To allow for some entrepreneurs to have zero outages, we assume that at the start of the period, each entrepreneur i draws a political connectedness shock, $q_i \in \{0,1\}$, which is independently and identically distributed across entrepreneurs. Fraction ρ of entrepreneurs draw $q_i = 1$, implying that they never experience an outage.

Endogenous generator access. As in the analytic model, entrepreneurs choose whether to produce in the traditional or the modern sector. If the entrepreneur chooses to operate in the modern sector, then she must pay an entry cost, $A\Omega$, that scales with productivity, $A \equiv A^T$ (Bollard, Klenow, and Li, 2016). In addition, entrepreneurs that choose to operate in the modern sector must also decide whether to operate a generator.

We assume that entrepreneurs maximize profits plus an idiosyncratic taste shock. Entrepreneurs draw a separate taste shock for each production option: traditional, modern with generator, and modern without generator. The taste shocks are independently and identically distributed across entrepreneurs and the three production options. At the start of each period, the entrepreneur draws the values of her three taste shocks from a Type-1 extreme value distribution with scale parameter ζ. The rationale for the taste shocks is that idiosyncratic factors outside of our model can affect an entrepreneur's sector decision, such as preferences for particular location (e.g., urban versus rural) or for particular types of tasks (e.g., farming versus sewing).

Each entrepreneur endogenously chooses the production option for which the sum of profits (net of the entry cost) and the taste shock is highest:

$$\pi_i + x_i = \max\left\{\pi^T(q_i,z_i) + x_i^T, \quad \pi^{M,N}(q_i,z_i) - A\Omega + x_i^{M,N}, \quad \pi^{M,S}(q_i,z_i) - A\Omega + x_i^{M,S}\right\}. \tag{9}$$

Superscript pairs M,N and M,S denote the modern sector without generator access and the modern sector with generator access, respectively. Variables x_i^T, $x_i^{M,N}$, and $x_i^{M,S}$ denote the realizations of the sector-specific taste shocks for entrepreneur i. Exploiting the properties of the Type-1 extreme value distribution implies that the probability an entrepreneur with political connectedness q_i and productivity z_i chooses to operate in the traditional sector equals:

$$\text{Prob}^T(q_i,z_i) = \frac{\exp(\zeta^{-1}\pi^T(q_i,z_i))}{\exp(\zeta^{-1}\pi^T(q_i,z_i)) + \exp(\zeta^{-1}\pi^{M,N}(q_i,z_i) - A\Omega) + \exp(\zeta^{-1}\pi^{M,S}(q_i,z_i) - A\Omega)}.$$

The corresponding expressions for the probability that the entrepreneur chooses to operate in the modern sector without a generator and in the modern sector with a generator are analogous. The scale parameter, ζ, affects the importance of the taste shocks for the entrepreneur's sector and generator choices. As ζ approaches infinity, the taste shocks become the only factor that affects the entrepreneur's sector and generator decisions.

Grid electricity production. We design a simple model of grid electricity production that captures the key features of electricity markets in developing countries discussed in Section 2, specifically the low electricity prices and frequent outages. We abstract from other aspects of electricity production, such as the degree of market power, different sources of electricity, and distinctions between generation, transmission, and distribution. These are important issues for some questions, but are not first order for our analysis.

There are measure one of electricity producers. Each electricity producer produces electricity from land, b_t, and grid capital, k_t^G, according to the production function:

$$e_t^G = A^G (k_t^G)^{\psi} b_t^{1-\psi}. \tag{10}$$

Parameter ψ denotes capital's share in grid-electricity production. The supply of land useful for electricity (e.g., hydro dam sites) is fixed and owned by the government. The electricity producers pay a licensing fee, Q_t, for each unit of land.

The electricity producer chooses grid capital, k_t^G, and land, b_t, to maximize profits, taking as given the grid electricity price, the licensing fee, and the rental rate for grid capital. Profits for each grid-electricity producer are:

$$\pi_t^G = P^G A^G (k_t^G)^{\psi} x^{1-\psi} - R_t k_t^G - Q_t b_t. \tag{11}$$

We assume that in equilibrium, the government sets the licensing fee, Q_t, so that the fixed supply of land is used at full capacity and all electricity producers earn zero profits (though this assumption is not central to our results). We normalize the supply of land to unity. The electricity producer's demand for grid capital and supply of grid electricity equal:

$$k_t^G = \left(\frac{\psi P^G A^G}{R_t} \right)^{\frac{1}{1-\psi}} \quad \text{and} \quad e_t^G = (A^G)^{\frac{1}{1-\psi}} \left(\frac{\psi P^G}{R_t} \right)^{\frac{\psi}{1-\psi}}. \tag{12}$$

The key implication of equation (12) is that electricity producers respond to an increase in P^G by raising their supply of electricity. The aggregate demand for grid capital and the aggregate supply of grid electricity equal the respective sums of capital demand and supply by each identical electricity producer: $K_t^G \equiv \int_0^1 k_t^G = k_t^G$ and $E_t^G \equiv \int_0^1 e_t^G = e_t^G$.

In line with the evidence discussed in Section 2, the government sets the grid-electricity price, P^G, at a value below that which would clear the grid-electricity market. Therefore, the price, P^G, does not clear the electricity market as it would in a standard competitive model. Instead, the probability that the power is on, v_t, adjusts endogenously to ensure that the total supply of grid electricity equals the total rationed demand for grid electricity. In particular, v_t solves:

$$\begin{aligned} E_t^G = v_t \int_t^{\infty} \left[e_t^{M,N}(0,z) J^{M,N}(0,z) + e_t^{M,S}(0,z) J^{M,S}(0,z) \right] dG(z) \\ + \int_1^{\infty} \left[e_t^{M,N}(1,z) J^{M,N}(1,z) + e_t^{M,S}(1,z) J^{M,S}(1,z) \right] dG(z). \end{aligned} \tag{13}$$

We use the notation $J^{M,N}(q,z)$ and $J^{M,S}(q,z)$ to denote the fractions of entrepreneurs with political connectedness q and productivity z that choose to operate in the modern sector without a generator and in the modern sector with a generator, respectively. If the government raises the grid-electricity price, then equation (12) implies that electricity producers increase production, raising the supply of grid electricity. Holding demand constant, the increase in electricity supply raises the probability of grid power, v_t, that solves equation (13). On the demand side, the increase in the price of grid electricity reduces grid-electricity demand, while the increase in the probability of grid power operates though the firm-expansion and firm-entry channels to increase grid-electricity demand. In general equilibrium, the probability of grid power that solves equation (13) for each grid-electricity price depends on both the supply- and demand-side factors.

5. Calibration

We calibrate the model to provide quantitative estimates of the effects of power outages on output per worker and the contribution of the different general equilibrium channels. We analyze four major Sub-Saharan African economies: Ghana, Nigeria, Tanzania, and Uganda. We choose these economies because they have frequent outages and because there is substantial private participation in electricity markets (Eberhard et al., 2011), suggesting that our model of the private provision of grid electricity is appropriate.[5] More generally, we focus on Sub-Saharan Africa because countries in this region have some of the most widespread power outages (Figure 1), policymakers are actively working to improve electricity supply (Eberhard et al., 2011), and relatively few economics papers study Sub-Saharan Africa compared to other developing economies.

Importantly, our calibrated model yields a positive correlation between generator ownership and firm size, as reported in much of the empirical literature (Alby et al., 2013; Foster and

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[5] A previous version of this paper also included Ethiopia:; we dropped Ethiopia in this version since its power is entirely publicly provided.

Steinbuks, 2008). In our model, firms with generators tend to be larger than those without because, on average, firms with higher productivity draws choose to purchase generators and because generator ownership endogenously increases productivity by reducing idle resources during and outage.[6] These dynamics allow our model to replicate the empirical regularity that relatively more large firms have generators.

Nigeria has the most detailed data of the four countries in our study, and so we first compute a baseline calibration using data from the Nigerian economy. We recalibrate TFP and several key parameters to match targets specific to each country in our study. The time period in the model is one year. We report all monetary values in year 2014 US dollars. We relegate the description of the data sources to Appendix C.

Baseline calibration for the Nigerian economy. We choose some parameters directly from the data and existing literature. Given these externally calibrated parameters, we choose a second set of parameters such that moments in the model match their empirical targets. Table 1 reports the values of the externally calibrated parameters.

Table 1: Parameter Values: Externally Calibrated Parameters

η	α	A^T	ϕ	δ	A^G	ψ	σ	β
0.85	0.33	1	1.4	0.06	1	0.7	2	0.96

Note: This table reports the baseline parameter values that we take from existing estimates.

We set the span-of-control parameter, η, equal to 0.85, as in Midrigan and Xu (2014). We use one third for capital's share in the capital-labor composite, $\alpha = 0.33$. We set the depreciation rate, the CRRA coefficient and the discount rate equal to standard values of 0.06, 2 and 0.96, respectively.

We are not aware of any empirical estimates of the price elasticity grid electricity, which would help pin down the value of ψ. Electricity market regulation and the simultaneity of supply and demand shocks make this elasticity difficult to identify empirically, even in developed economies. Instead, we choose $\psi = 0.7$ to reflect the relatively high capital share in electricity in the data. Section 6 reports the sensitivity of the main results to alternative values of ψ.

We normalize grid productivity, A^G, and traditional productivity, A^T, both to unity. Modern productivity parameter, ϕ, determines the productivity boost an entrepreneur receives by switching to the modern production technology. We set $\phi = 0.4$, in line with the productivity difference between the traditional and modern sectors in Midrigan and Xu (2014). Consistent with

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[6] Generator ownership also increases idle resources when the power is on. In equilibrium, the productivity gains from the reduced idle resources when the power is off exceed the productivity losses from the increased idle resources when the power is on.

this choice, Lagakos (2016) finds that the productivity of the modern segment of the retail sector is on average 43 percent larger than the productivity of the traditional segment, based on data from six lower income economies. Section 6 explores the sensitivity of the main results to alternative values of ϕ and shows that the results are not as sensitive to this parameter as one might expect.

Table 2: Parameter Values: Internally Calibrated Parameters

μ	χ	A^S	P^G	Ω	λ	ζ	ρ
1.48	2.14	1.02	0.11	0.54	1.73	0.24	0.08

Note: This table reports the baseline parameter values that we choose to match the empirical targets.

We jointly calibrate the remaining parameters so that moments in the model match their empirical targets. Table 2 reports the resulting parameter values. We discuss each parameter and its primary target in turn. Appendix Table C.2 reports how a one percent increase in each parameter value affects each of the eight targets, where the parameter's primary targets lies on and near the diagonal.

The grid-electricity price, P^G, largely determines the level of grid capital, K^G, which in turn controls the supply of grid electricity. All else constant, the supply of grid electricity governs how much electricity firms can purchase from the grid and how much they must self-produce from generators. The WES report that Nigerian firms with generators self-generate 59 percent of their total electricity consumption. We choose the regulated level of the grid-electricity price, P^G, to match this target.

The ratio of the average cost of self-generated electricity (green columns of Figure 3) to the average cost of grid electricity (blue columns of Figure 3) pins down self-generation productivity, A^S. For grid electricity, the firm's average cost equals the marginal cost, P^G. However, for self-generated electricity, the average cost differs from the marginal cost because the firm must incur the fixed cost of renting the generator. To calculate the average cost of self-generated electricity, we add the variable cost calculated above to estimates of the capital and maintenance costs of a typical diesel generator (see Appendix C). The average cost of self-generated electricity equals 34 cents per kWh, 5.51 times larger than the average cost of grid electricity.

We choose parameters Ω, λ, and ζ to match three targets relating to the number of firms using each of the three production options (traditional, modern with generator, and modern without generator), and the relative sizes of those firms. Using data from Nigerian firm surveys, we find that the total modern sector (including firms with and without generators) employs 63 percent of workers and includes 30 percent of firms. Additionally, the Nigerian WES reveals that 82 percent of modern firms that experience outages have access to generators.

The Leontief parameter in final goods production, μ, determines electricity's share of modern production. Allcott et al. (2016) estimate that electricity share equals 7.4 percent of value added among Indian manufacturing firms.[7] Since, electricity expenditures include expenditures on both grid and self-generated electricity, the probability of grid power could affect the electricity share. Furthermore, the probability of grid power in the Nigerian economy likely differs from Allcott et al. (2016)'s reported probability of 0.93 for Indian manufacturing firms. To align our model as closely as possible with the empirical target, we choose μ so that modern electricity share equals 7.4 percent in a counterfactual steady state in which the probability of grid power in Nigeria equals 0.93.

Lastly, the WES data reveal that 20 percent of modern firms in Nigeria never experience outages. We choose ρ, the probability that an entrepreneur in the model (who could choose to be modern or traditional) never experiences an outage, to match this target. Appendix Table C.1 reports the values of the moments in the model and the data. The model matches the targeted moments out to four decimal places.

Country-specific calibration. Consistent with much of the macro literature, we assume that the production functions for modern and traditional output and for grid electricity are the same across countries. Ideally, we would re-calibrate the entry cost, Ω, and the distribution parameters, λ and ζ, to match country-specific targets on the number and size of firms using the traditional technology, the modern technology with a generator, and the modern technology without a generator. However, the firm surveys reporting the number and size of all modern firms are only available for Nigeria. Given this data constraint, we assume that Ω and λ are the same across countries. We use the country-specific data to re-calibrate ζ, along with TFP, A^T, self-generation productivity, A^S, and fuel efficiency, χ, the price of grid electricity, P^G, and the fraction of entrepreneurs that do not experience outages, ρ, for each country in our study (see Appendix C).

Our calibrated model does well at matching several features of the data that we do not specifically target. First, the empirical evidence suggests that firms with generators are larger than those without. Using the WES data, we regress generator ownership on the log of firm size in each country. The first column of Table 3 reports the estimated semi-elasticity in each country and with the 95 percent confidence interval in brackets. The second column of Table 3 reports corresponding semi-elasticity in our model. Among the firms that experience outages in our model, those with generator access endogenously choose a larger scale than those without, allowing the model to replicate the positive semi-elasticity of generator ownership with respect

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[7] Similarly, Fisher-Vanden et al. (2015) find that the electricity share of value added equals 6 percent among Chinese manufacturing firms.

to firm size. The magnitude of the semi-elasticity is similar between the model and the data, though it is slightly larger in the model in all countries. In Section 6, we show that this slightly larger semi-elasticity does not substantially affect the model's quantitative predictions.

Table 3: Semi-Elasticity of Generator Ownership With Respect to Firm Size

	Data	Model
Ghana	0.12	0.35
	[0.07, 0.17]	
Nigeria	0.04	0.09
	[-0.04, 0.12]	
Tanzania	0.06	0.10
	[-0.004, 0.13]	
Uganda	0.05	0.24
	[-0.07, 0.16]	

Note: For each country, the first column reports estimated semi-elasticity of generator ownership with respect to firm size from the WES data. The square brackets below each estimate are the 95 percent confidence intervals. The second column reports the corresponding semi-elasticity in the model.

Additionally, in Section 7 we conduct firm-level surveys in Ghana and Nigeria to validate our two main general equilibrium channels. Consistent with our model, we find that the majority of modern-sector business owners in both countries believe that eliminating outages would cause them scale up production and cause more firms to enter their sector.

6. Quantitative Results

In our main experiment, we simulate the effects of eliminating outages by letting the price of grid electricity adjust to clear markets.[8] Introducing a market-clearing electricity price is a purely counterfactual exercise in the sense that no African country has implemented such a reform (Eberhard et al., 2011). Hence, our model provides the necessary laboratory to explore how increasing the electricity price to eliminate outages would affect output, consumption, and other macroeconomic aggregates.

Long-run general-equilibrium effects of eliminating power outages. To quantify the long-run general-equilibrium effect of eliminating outages in each country, we compare the country's initial calibrated steady state with a counterfactual "no-outages" steady state. In the no-outages steady state, we de-regulate the electricity market by allowing the price to adjust so that grid-

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[8] Note that this experiment involves raising price as well as increasing the reliability of the grid. Raising the price alone has negative effects on firms in the model, since it raises production costs and reduces output. This is consistent with the empirical findings of Abeberese (2017), who documents that higher electricity prices for Indian manufacturing firms resulted in lower output and labor productivity growth.

electricity supply exactly equals demand. The resulting increase in the grid-electricity price eliminates outages by increasing the supply of grid capital and grid electricity (equation 12). Table 4 reports the electricity price, electricity capital, and electricity supply in the no-outages steady state relative to their values in the initial steady state for each country. The levels of each variable in the initial steady state, along with the probability of grid power, are reported in Appendix D. Eliminating outages requires substantial increases in grid-electricity prices in all four countries, ranging from 18 percent in Uganda to 45 percent in Nigeria. The higher grid electricity prices lead to considerable increases in grid electricity capital, which, in turn, raises grid electricity supply.

Table 4: Grid Electricity Price, Capital, and Supply
(Value relative to initial steady state)

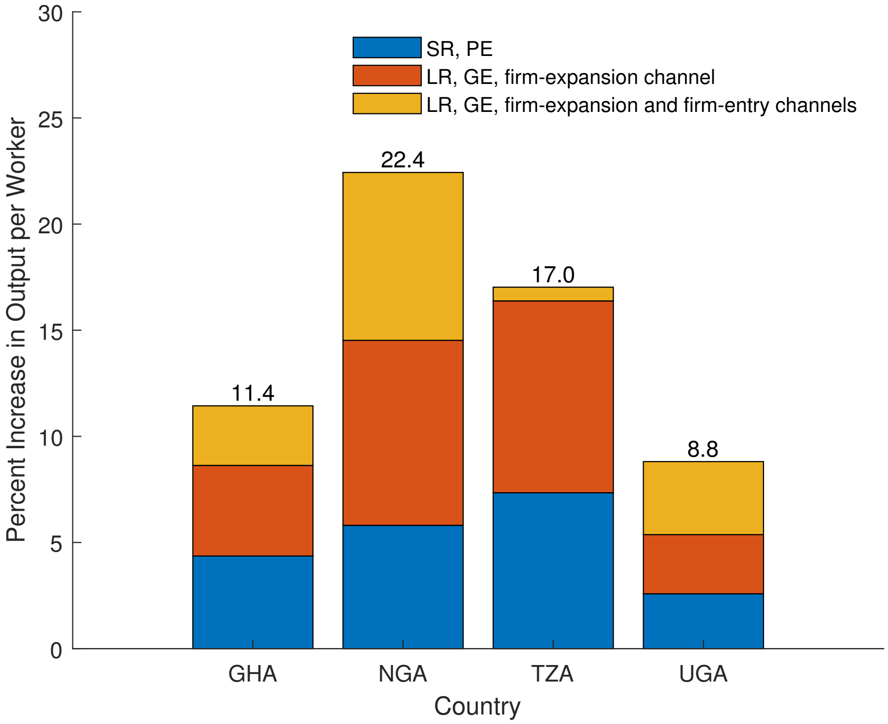
	Grid price: P^G	Grid capital: K^G	Grid electricity: E^G
Ghana	1.19	1.76	1.49
Nigeria	1.45	3.43	2.37
Tanzania	1.20	1.83	1.53
Uganda	1.18	1.75	1.48

Note: Column (1) the grid-electricity price necessary to eliminate outages relative to its value in each country's initial steady state. Columns (2) and (3) report the corresponding levels grid-electricity capital and supply, relative to their values in each country's initial steady state.

Figure 6 plots the long-run general-equilibrium effect of eliminating outages. Eliminating outages leads to large increases in output per worker in all countries, ranging from 8.8 percent in Uganda to 22.4 percent in Nigeria. Ghana, and Tanzania are in the middle, with increases in output per worker equal to 11.4 and 17.0 percent, respectively. Averaging across all four countries, eliminating outages increases output per worker in the long-run general equilibrium by approximately 15 percent.

To better understand the sources of productivity gains from eliminating outages, we decompose the total increase in output per worker into three components, corresponding to the three sections of each bar in Figure 6. The blue section shows the short-run partial-equilibrium effect, which is the increase in output per worker that results when outages are eliminated ex-post, after entrepreneurs have already made their scale, sector, and generator decisions. Specifically, we hold constant prices, firm size, and the distribution of firms across the traditional sector and the modern sector with and without a generator. We then compute output per worker if the probability of grid power equals one, instead of its value in the initial steady state. This exercise is truly partial equilibrium in the sense that we do not require the markets for capital, labor, or electricity to clear.

Figure 6: Long-Run General-Equilibrium Effects of Eliminating Power Outages



Note: The height of each bar equals the total steady-state increase in output per worker from eliminating power outages in each country. The blue, orange, and yellow regions of each bar correspond to the relative contributions from the short-run partial-equilibrium effect, the firm-expansion channel and the firm-entry channel, respectively.

Consistent with the microeconomic evidence (e.g., Allcott et al., 2016, and the other studies cited in the introduction), the short-run partial-equilibrium effects of eliminating outages are small, ranging from 2.6 percent in Uganda to 7.3 percent in Tanzania. Averaging across all four countries, eliminating outages in the short-run partial equilibrium only increases output per worker by approximately 5 percent. Comparing the short-run partial-equilibrium effect with the long-run general-equilibrium effect (equal to the full height of each bar in Figure 6) reveals that the long-run general-equilibrium effects are three times larger, on average. Hence, as Buera et al. (2019) also find in the microfinance context, the short-run partial equilibrium effect is an important component of the total macroeconomic impact, but it is far from the whole story.

The large long-run effects do not result from large (counterfactual) short-run effects, but instead from the additional increases in output per worker generated by the firm-expansion and firm-entry channels. The orange and yellow sections of each bar represent the increase in output per worker from adding the firm-expansion and firm-entry channels, respectively. To isolate the effects of the firm-expansion channel (orange sections), we solve for a no-outages steady state in which the distribution of entrepreneurs across the three production options is fixed at its value in the initial steady state. In this exercise, all markets clear, but entrepreneurs' sector and generator decisions are not necessarily optimal. The additional increase in output per worker from the firm-entry channel (yellow sections) equals the difference between the no-outages steady state and the no-outages steady state with the distribution of entrepreneurs across production options fixed at its value in initial steady state. As Figure 6 shows, both the firm-entry and the firm-expansion channels lead to substantial increases in output per worker.

Table 5: Effects of Eliminating Outages on Macro Aggregates
(percent change from the initial steady state)

	Ghana	Nigeria	Tanzania	Uganda
Modern entrepreneurs: Q^M	23	66	2	35
Modern labor: N^M	15	45	18	24
Wage rate: W	12	20	15	6
Modern productive capital: K^M	29	74	36	31
Traditional capital: K^T	-48	-69	-44	-33
Aggregate capital stock: K	9	24	18	10
Measured TFP: $Y/(\tilde{K}^{\alpha}N^{1-\alpha})$	8	14	11	5
Consumption: C	10	17	22	6

Note: This table reports the percent change in a number of variables in the no-outages steady state from their corresponding values in the initial steady state. Measured TFP equals aggregate output divided by a Cobb-Douglas aggregate of measured capital and labor, $\tilde{K}^{\alpha}N^{1-\alpha}$, where α equals 0.33. Measured capital, $\tilde{K}$, equals the aggregate capital stock plus entry costs.

To quantify the broader macroeconomic consequences of eliminating outages in each country, Table 5 reports the percent change in a number of variables in the no-outages steady state relative to their values in the initial steady state. Eliminating outages leads to substantial increases in the size of the modern sector, measured either by the number of modern firms, Q^M, or by the number of modern workers, N^M (first two rows of Table 5). Since the total numbers of firms and workers are fixed, the increases in the numbers modern firms and workers generate parallel decreases in the numbers of traditional firms and workers.

Eliminating outages leads to large increases in the equilibrium wage, ranging from 6 percent in Uganda to 20 percent in Nigeria (third row of Table 5). The reason for the increase in wages is that the number of modern firms increases and existing modern firms rent additional capital and purchase more electricity, all of which increase the marginal product of labor. The rental rate of capital is pinned down entirely by the household-Euler equation and is thus unchanged, as in the analytic version of the model in Section 3. Productive capital in the traditional and modern sectors moves in opposite directions (fourth and fifth rows of Table 5). The combined effects of the firm-expansion and firm-entry channels lead to substantial increases in productive capital in the modern sector. Capital in the traditional sector falls both because the firm-entry channel implies that there are fewer traditional firms and because the higher wages cause traditional firms to hire fewer workers, reducing their demand for capital.

The final three rows of Table 5 report the effects of eliminating outages on the aggregate capital stock, measured TFP, and consumption. Following the development accounting literature (Hall and Jones, 1999; Caselli, 2005), we define measured TFP as aggregate output, Y, divided by a Cobb-Douglas aggregate of measured capital and labor, $\tilde{K}^{\alpha}N^{1-\alpha}$, where α equals the calibrated value of capital share, 0.33. To be conservative, we define measured capital, $\tilde{K}$, to equal the aggregate capital stock plus entry costs, which can be thought of as a type of capital.

Eliminating outages leads to substantial increases in the aggregate capital stock, ranging from 9 percent in Ghana to 24 percent in Nigeria, implying that capital accumulation is an important driver of the gains in output per worker reported in Figure 6. However, the increases in output per worker do not result from capital accumulation alone. We also see large increases in measured TFP, ranging from 5 percent in Uganda to 14 percent in Nigeria. Eliminating outages increases measured TFP because it eliminates idle resources and because it shifts entrepreneurs to the more-productive modern sector. The higher steady-state capital stock and measured TFP generate substantial increases in consumption.

Sensitivity. To provide insights on the underlying mechanisms driving the quantitative results, we explore the sensitivity of the results for the Nigerian economy to the following parameter values and targets: (1) capital's share in grid electricity production, ψ, (2) the productivity boost from becoming modern, ϕ, (3) grid-electricity's share in modern production, (4) the average and marginal costs of self-generated electricity and (5) the fraction of modern entrepreneurs that do not experience outages. In each case, we re-calibrate all the parameters in the Nigerian economy to either match the new set of targets or to account for the change in the directly calibrated parameter value. The five panels of Table 6 report the effect of eliminating outages on output per worker in the long-run general equilibrium, (first column) and in the short-run partial equilibrium (second column). The middle row in every panel corresponds to the baseline calibration. Comparing the first and second columns reveals that in every sensitivity exercise, the long-run general equilibrium effect of eliminating outages is over three times larger than the short-run partial equilibrium effect.

Higher values of the capital share in grid-electricity production, ψ, imply weaker diminishing returns in grid-electricity production. As a result, de-regulating the electricity market leads to a smaller increase in the grid-electricity price and a larger increase in the grid-electricity supply, magnifying the gains in output per worker. Higher values of the modern productivity boost,

Table 6: Sensitivity to Parameter Values and Targets

	Percent increase in output from initial steady state	
	Long run, G.E.	Short run, P.E.
Capital share in grid-electricity production: ψ		
$\psi = 0.6$	18.8	5.0
$\psi = 0.7$	22.4	5.8
$\psi = 0.8$	26.6	6.7
Modern productivity boost: ϕ		
$\phi = 0.3$	19.6	5.6
$\phi = 0.4$	22.4	5.8
$\phi = 0.5$	25.5	5.3
Electricity share of modern output		
Share = 0.06	18.6	4.6
Share = 0.074	22.4	5.8
Share = 0.09	28.0	6.9
Self-generation costs		
10 percent decrease in costs	20.0	5.3
Baseline costs	22.4	5.8
10 percent increase in costs	25.2	6.4
Fraction of modern firms with no outages		
Fraction = 0.1	22.3	6.9
Fraction = 0.2	22.4	5.8
Fraction = 0.3	21.9	4.6

Note: This table reports the long-run general equilibrium (first column) and short-run partial equilibrium (second column) percent increase in aggregate output between the initial and no-outages steady states in the Nigerian economy. The five panels correspond to perturbations of the capital share in grid-electricity production, the modern productivity boost, the electricity share of modern output in the counterfactual steady state with $\nu = 0.93$, the self-generation costs, and the fraction of modern firms that do not experience outages. The middle row in every panel is the baseline calibration.

ϕ, increase the gains in output per worker from the firm-entry channel, raising the total increase in output per worker. However, the impact of changes ϕ are smaller that one might expect because the model must match the same empirical targets in the initial steady state. For example, all else constant, higher values of ϕ make the modern sector more attractive, increasing the size and number of modern firms. Consequently, matching the empirical shares of modern labor and firms with a higher value of ϕ requires a larger entry cost, Ω, and a larger Pareto distribution parameter, λ. The larger values of Ω and λ partially offset the impact from the larger value of ϕ on the increase in output per worker from eliminating outages.

As one might expect, the effects of eliminating outages depend on electricity's share of modern output, which determines the relative importance of electricity as a production input, and on the costs of self-generation, which determines the cost of electricity during an outage. At the extreme lower bound, if electricity did not enter modern production at all (so that its share equaled zero) or if the cost of self-generation equaled the cost grid electricity, then eliminating outages would have no effect on output per worker. Increasing either of these variables from this lower bound necessarily increases the long-run general-equilibrium effects of eliminating outages. Importantly, the values used in the baseline calibration for electricity's share of modern output and the self-generation costs are disciplined by direct empirical evidence from developing economies. Thus, while the actual values could always differ, in practice, we expect that they will be relatively close to the baseline calibration.

Increases in the fraction of modern firms that do not experience outages reduces the semi-elasticity of generator ownership with respect to firm size. The semi-elasticity falls from 0.2, to 0.09, to 0.05, as the fraction of modern firms that do not experience outages increases from 0.1 to 0.2 to 0.3. Importantly, the long-run general equilibrium increase in output per worker equals approximately 22 percent across all three perturbations, implying that the magnitude of the semi-elasticity does not have substantial effects on our results.

Insights on weak links, aggregate productivity, and electricity taxes. The regulated electricity price and resulting outages in our model are fundamentally different from other causes of low electricity supply, such as low productivity in electricity production or a tax on electricity producers. Insights from the previous literature (Jones, 2011) imply that if output from a low-productivity or taxed sector is sufficiently scarce, then its price will rise to attract more inputs, thus raising output in that sector. In our context, with electricity rationed through power outages, these forces do not operate in the same way. The electricity price is regulated to be artificially low, which prevents resources from reallocating to the electricity sector and, as a result, outages can more severely constrain aggregate output.

To illustrate the how the effects of power outages differ from low productivity in the electricity sector, Figure 7 plots the responses of output per worker and grid-electricity capital per worker to an electricity supply shock in our outages economy (solid green line) and in a competitive economy in which the grid-electricity price adjusts to clear the market (dashed blue line). The right-most point in both panels corresponds to the no-outages steady state for Nigeria. Moving from right to left along the outages-economy line, we reduce the price of grid-electricity so that total electricity supply (grid plus self-generated) in steady state decreases by the amount on the x-axis, causing outages to become more frequent. The left-most point corresponds to the initial steady state in the Nigerian economy.[9]

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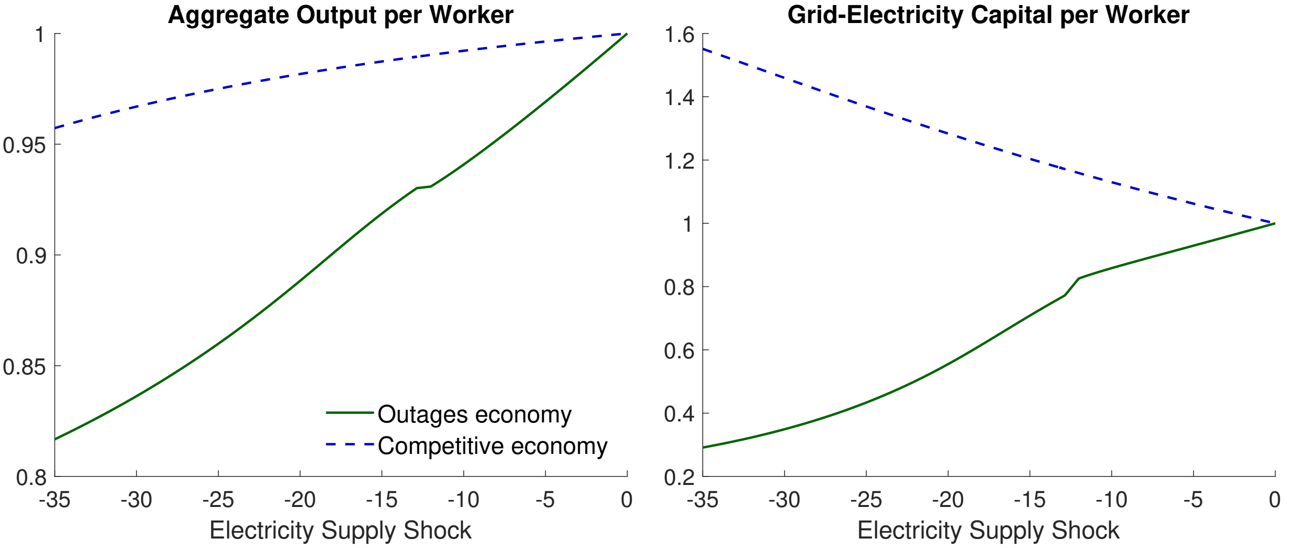
[9] In a small region around $v^{\star}$, there are two different steady states that generate the same amount of grid-

Figure 7: Competitive Economy versus Outages Economy



Note: This figure plots the responses of output per worker and grid-electricity capital per worker in Nigeria to an electricity supply shock in our outages economy (solid green line) and in a competitive economy (dashed blue line). The right-most point on the solid green line in both panels corresponds to the counterfactual no-outages steady state for Nigeria and the left-most point corresponds to the initial steady state. Moving from right to left along the outages-economy (solid green) line, we reduce the price of grid-electricity so that total electricity supply (grid plus self-generated) in steady state decreases by the amount on the x-axis. Moving from right to left along the dashed blue line, we reduce productivity in grid-electricity production, A^G, by the percentage on the x-axis.

Moving from right to left along the dashed blue line, we conduct a similar exercise for the competitive economy by reducing productivity in grid-electricity production, A^G, by the percentage on the x-axis. This exercise results in higher grid-electricity prices, but no outages, because the price endogenously adjusts to clear the grid-electricity market.

The electricity-supply shocks lead to larger decreases in output per worker in the outages economy than in the competitive economy; moving from right to left in the left panel of Figure 7, the solid green line falls farther below the dashed blue line. Indeed, at the initial steady state (left-most point on the x-axis), output per worker falls by almost 20 percent in the outages economy but by less than 5 percent in the competitive economy. The reason for the difference is that in the competitive economy, the endogenous increase in the grid-electricity price attracts more capital to the grid-electricity sector, which substitutes for the low productivity and thus alleviates the constraints on aggregate output. In contrast, in the outages economy, the artificially low grid-electricity price causes capital to leave the grid-electricity sector, reducing supply and

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electricity supply, one in which $\nu < \nu^\star$ and relatively more electricity comes from generators and one in which $\nu > \nu^\star$ and relatively more electricity comes from the grid. As a convention, we plot only the steady state with $\nu < \nu^\star$ when there are two steady states. Plotting instead only the steady state with $\nu > \nu^\star$ when there are two steady states does not meaningfully change the graph.

creating outages. The right panel of Figure 7 illustrates these opposite responses; moving from right to left, grid-capital per worker increases in the competitive economy (dashed blue line) and decreases in the outages economy (solid green line).

We can apply the same intuition to understand how outages are different from a tax on electricity suppliers. Figure D.1 in Appendix D plots the results from an experiment analogous to the one described above, except with a tax on electricity producers. The endogenous increase in the electricity price in response to the tax means that less capital leaves the electricity sector in the taxed economy, compared to the outages economy. As a result, the decline in output per worker in the taxed economy is much smaller than in the outages economy.

In sum, the distortions in the electricity sector, caused by artificially depressed prices, fundamentally differ from those caused by low sector productivity or a tax in an otherwise competitive economy. Competitive forces can alleviate the consequences of tax distortions and low productivity by raising the price to attract more resources to the affected sector. But competitive forces cannot alleviate the consequences of depressed prices since, by design, the price cannot adjust to reflect the true scarcity of the input. Instead, the depressed prices discourage investment in electricity production, resulting in shortages. Thus, as long as electricity prices are artificially low, the electricity sector is likely to severely constrain aggregate output.

7. Supporting Evidence

Our theory predicts that eliminating power outages would cause existing firms to expand their operations and new firms to operate better technologies that require electricity. In this section, we use two approaches to validate these two channels. First, we cite the existing empirical evidence on the effects of outages on firm expansion and firm entry. Second, we provide new survey evidence from firms in Ghana and Nigeria about the expected effects of permanently eliminating outages on their businesses and industries.

Existing evidence. It is challenging to empirically estimate the long-run general-equilibrium effect of eliminating outages because, to our knowledge, no developing country in the modern era has been able to eliminate outages for any significant period of time. Two studies that estimate related channels are by Reinikka and Svensson (2002) and Kassem (2020). Using cross-sectional data from 171 Ugandan firms, Reinikka and Svensson (2002) find that among firms without generators, those that experience more outages undertake less investment. They find no statistically significant effect for firms with generators. While the firm-expansion channel in our model implies that power outages reduce investment for modern firms with and without generators, the impact is considerably larger for firms without generators, consistent with Reinikka and Svensson (2002)'s findings.

Kassem (2020) exploits regional variation in the roll out of the Indonesian electric power grid to estimate the effects of grid connections on the size and structure of the manufacturing sector. She finds that access to the national electric grid increases both the number and size of manufacturing firms. In the context of our model, gaining access to the electric grid corresponds to an increase in the probability of grid power from zero to some positive number. Hence, we view her results as supporting the model's theoretical predictions that increases in the probability of grid power will cause existing firms to expand and new firms to enter.

New survey results from African firms. To supplement the existing empirical evidence, we survey firms about their expectations for what would happen if electricity outages were permanently eliminated. We do so using new surveys of business owners in Ghana and Nigeria. The main advantage of this approach is that we can directly ask firms in two of the countries we include in our analysis about the specific channels in our model.

Our surveys cover a sample of firm owners in Ghana and Nigeria, and were conducted from June to August 2019. We implemented the surveys with Google Surveys, a platform that allows users to survey a random sample of internet news readers. The readers are incentivized to take the survey by being offered free access to the remainder of their news article after completing the survey. Readers are also given the option to opt out of any survey. We identified business owners with an initial screening question about whether the respondent currently owned and operated a business. We then asked the business owners between three and six additional questions, depending on the survey. We ran a total of 34 surveys covering 3,425 firms, of which 1,913 were from Ghana and 1,512 were from Nigeria. The overall dropout rate was low after the initial screening question, at slightly less than 14 percent, and we kept only those responding to all questions, which was most of the respondents.

Not surprisingly, the business owners in our surveys were disproportionately educated and living in urban areas. In Ghana, for example, 89 percent of respondents had completed secondary school or more and 93 percent came from the largest two cities of Accra and Kumasi. One would not want to use these surveys to learn about rural farmers or entrepreneurs in the traditional sector in urban centers. Yet they may not be a bad approximation to those operating in the modern sector in our model, since modern-sector entrepreneurs in the model are those with the highest productivity levels.

Importantly, firms in our surveys were representative in that they reported regularly experiencing power outages and use of generators to self-produce power. When asked about the frequency of power outages in the last year, the most common answer in both countries was the maximum category, 10 or more times, with 46 percent of Nigerians and 23 of Ghanians selecting this answer. Just 23 percent of Ghanian firms and of 11 percent of Nigerian firms reported not having any outages in the last year. On average, 55 percent of firms in Ghana and 85 percent in Nigeria reported that they owned or had access to a generator. These statistics line up well with those from the World Bank Enterprise Surveys presented in Section 2. Firms in our survey are also consistent with World Bank Enterprise Surveys in their skewness toward smaller firm sizes relative to richer countries (see Appendix E), and their industry composition being primarily services and only partly manufacturing and agriculture.

To understand how eliminating power outages would affect firms in the developing world, we asked a series of hypothetical questions to the Ghanaian and Nigerian firm owners about their expectations for what would happen if outages were eliminated. We focused on four main outcomes: profits, expansion through investment, expansion through hiring, and entry of new firms in the same industry. For the first three questions we ask about the effects of eliminating power outages "for your firm" and for the last we specify that power outages would be eliminated in their country. For all questions we asked how likely the firms felt each outcome would be if power outages were eliminated, with the options being "very unlikely," "unlikely," "neutral," "likely," "very likely" and "I don't know."

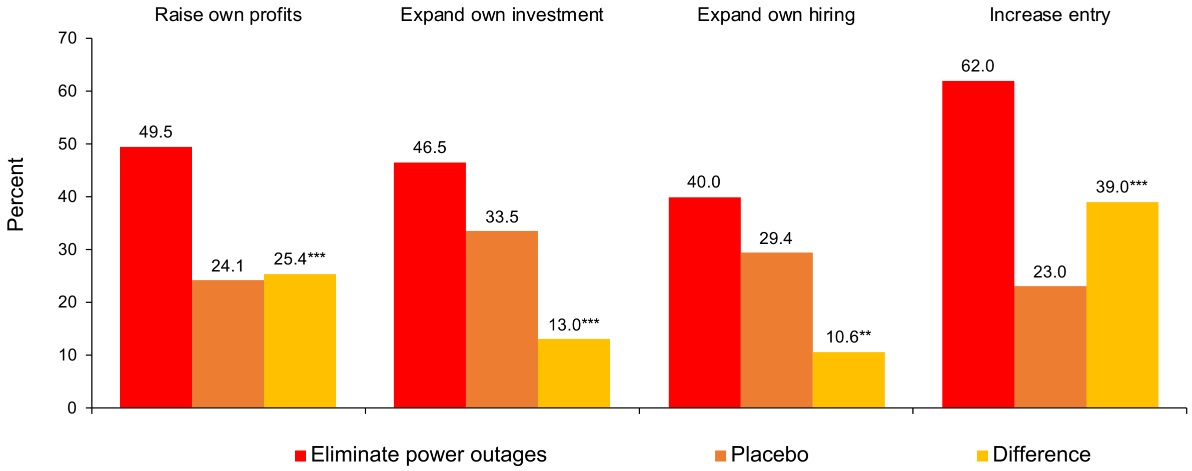
One potential limitation of any survey – and online surveys in particular – is that respondents may provide uninformative answers or answers based on what they expect the surveyors would like to hear. In order to measure how common this is among the respondents in our setting, we ran a series of surveys that asked firms about the expected effects of a placebo "treatment" in which the national airports in Ghana or Nigeria convert to solar power. The advantage of this placebo treatment is that it is a policy issue related to electricity, as in our main questions about eliminating power outages, but it would be quite unlikely to affect the vast majority of firms. In all of the surveys about the placebo treatment, we asked about exactly the same outcomes and used the exact same response options as the main surveys on power outages, so as to make apples-to-apples comparisons.

Figure 8 plots the percentage of firms responding that each outcome would be "likely" or "very likely" if power outages were permanently eliminated. As a frame of reference we plot the percentage responding that each outcome would be "likely" or "very likely" under the placebo treatment. We also plot the simple difference between the two percentages, and summarize the *p*-values of a test of the difference in the two proportions with three, two or one stars to represent significance at the 1-, 5- and 10-percent level. Panels (a) and (b) present the results from Ghana and Nigeria, respectively.

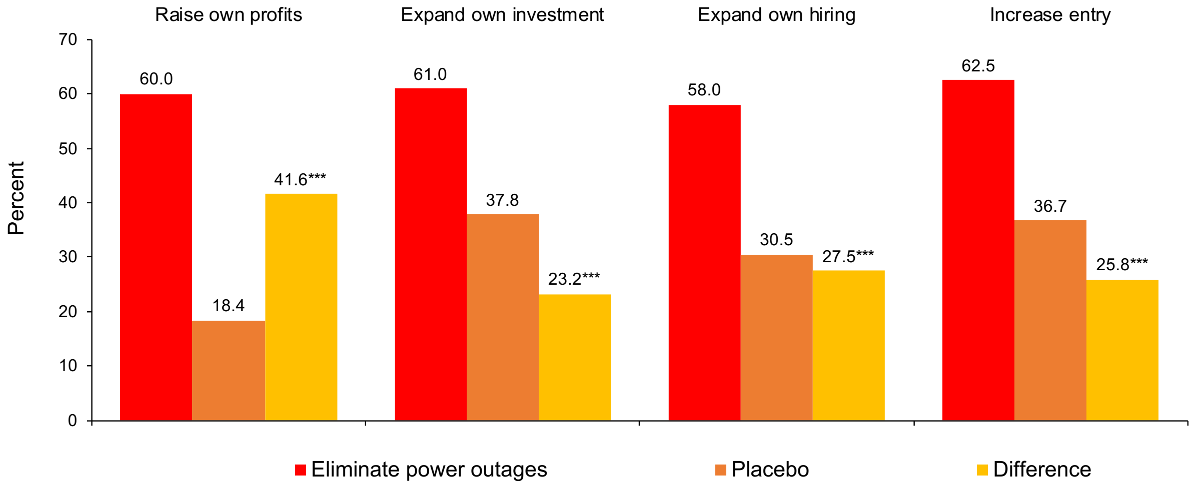
As Figure 8 shows, the majority of firms owners expect that eliminating power outages for their

Figure 8: Effects of Eliminating Power Outages from the Firms' Perspective

(a) Ghana



(b) Nigeria



Note: This figure plots the percent of firms answering that each effect is "likely" or "very likely" if power outages were permanently eliminated (red bars). The other choices are "very unlikely," "unlikely," "neutral" and "don't know." The frame of references is a placebo scenario in when the national airports would convert to solar power (orange bars). The difference is plotted (yellow bars) along with ***,** or * to represent the *p*-value of the test of the null hypothesis that the difference between eliminating power outages and the placebo is zero being less than 1 percent, 5 percent and 10 percent.

firm would raise profits and lead them to expand by making new investments and increasing hiring. Relative to the placebo treatment, 25.4 percent more Ghanaian firms and 41.6 percent more Nigerian firms expect that eliminating power outages would be "likely" or "very likely" to raise their profits. Firms in both countries were also significantly more likely to report that eliminating power outages would lead them to expand through increased investment or by increasing their hiring. These differences are all statistically significant at the 5-percent level or lower. These results provide support for the model's qualitative predictions that permanently eliminating power outages would lead firms to expand.

The last columns of Figure 8 report the firms' expectations for how eliminating power outages would affect the entry of new firms into their industries. Relative to the placebo, 39 percent more Ghanaian firms report that eliminating power outages would be likely or very likely to increase entry. In Nigeria, it is 25.8 percent more firms. Both are statistically significant differences, suggesting that firms do expect that eliminating outages would increase entry, as our model predicts.

8. Conclusion

Unreliable electricity is widely thought by policymakers to be a major constraint on firm productivity in the developing world. Yet most empirical studies of how power outages affect firm performance conclude that eliminating outages would lead to very modest productivity increases. Our paper is the first to model and quantify the long-run general-equilibrium effects of eliminating power outages. In contrast to the previous literature, we find that eliminating outages generates large increases in aggregate output per worker across the four Sub-Saharan African countries in our study, on the order of 15 percent. Through the lens of development accounting, eliminating outages works through increases in aggregate capital per worker, as firms expand, and through increases in TFP, as fewer productive resources are idled and more firms operate with more-productive, electricity-using technologies.

Our model abstracts from several mechanisms through which electricity could increase output per capita, implying that our quantitative results may be a lower bound. First, temporary outages may permanently damage production. The production of semiconductors represents one extreme, in which a split-second interruption in the power supply reportedly damaged chips that take weeks to produce (Clark and Osawa, 2010). These potential disruptions imply that frequent power outages could deter some industries, such as semiconductors, from locating in a country altogether. On the household side, electricity may also raise labor supply through the adoption of time-saving home appliances (Dinkelman, 2011; Gertler, Shelef, Wolfram, and Fuchs, 2016) or encourage human capital accumulation (Vidart, 2020). Future work should explore other channels through which electricity raises income levels in the long run.

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Appendix: For Online Publication Only

A. Solution to the Analytic Version of the Model

Proof of Proposition 1: For firms with and without generator access, the result that capital demand is increasing in the probability of grid power follows directly from the first order condition for capital. We focus instead on understanding the cutoff, $v^{\star}(R_t)$, below which firms with generator access purchase enough generator capital to operate at full capacity during an outage.

The firm always idles generator capital when the power is on because the price of grid electricity is zero, and this is lower than the marginal cost of fuel to operate the generator (which equals unity). Whether the firm idles productive capital when the power is off depends critically on whether the constraint that $k_t^S \leq k_t^M$ binds. We show that this constraint binds for all values of v less than the cutoff, $v^*(R_t)$, which we will characterize below.

The modern firm's first order conditions for k_t^S, and k_t^M from (6) are:

$$k_t^S: \quad \eta(1-v_t)A^M z^{1-\eta}(k_t^S)^{\eta-1} = R_t + 1 - v + \theta \tag{14}$$

$$k_t^M: \quad \eta v A^M z^{1-\eta}(k_t^M)^{\eta-1} + \theta = R_t, \tag{15}$$

and the complementary slackness condition requires that:

$$\theta\left(k_t^M - k_t^S\right) = 0. \tag{16}$$

When the constraint does not bind, the solutions are:

$$k_t^M = z\left(\frac{v\eta A^M}{R_t}\right)^{\frac{1}{1-\eta}} \quad \text{and} \quad k_t^S = z\left[\frac{(1-v)\eta A^M}{R_t+1-v}\right]^{\frac{1}{1-\eta}}. \tag{17}$$

The constraint does not bind as long as $k_t^M > k_t^S$. Substituting in the expressions for k_t^S and k_t^M from equation (17) implies that the constraint will not bind as long as,

$$\frac{v}{R_t} - \frac{1-v}{R_t+1-v} > 0. \tag{18}$$

The left-hand side of equation (18) *is increasing in* v. Define $v^*(R_t)$ to be the value of v that makes (18) hold with equality given R_t. When $v < v^*(R_t)$, the constraint binds and the firm rents enough generator capital to operate at full capacity when the power is off. As a result, there are zero idle resources during instants without power. When $v \geq v^*(R_t)$, the constraint does not bind and the firm rents less generator capital that what is required to operate her productive capital. In this case, she must idle some productive capital when the power is off. Power outages are entirely responsible for the existence of idle resources. When there are no power outages, $v=1$, and equation (17) implies that generator capital equals zero. Zero generator capital combined with zero instants without power results in zero idle resources. $\square$

Modern sector entry: We show that the difference in expected profits, $E(\pi^M(z))-\pi^T(z)$ is increasing in z. The difference in expected profits for a given entrepreneur with productivity z equals:

$$E(\pi^M(z))-\pi^T(z)=\gamma\pi^M(1,z)+(1-\gamma)\pi^M(0,z)-\pi^T(z)$$

Substituting in the relationship that profits equal fraction $1-\eta$ of output yields:

$$E(\pi^M(z))-\pi^T(z)=(1-\eta)[\gamma y_t^M(1,z)+(1-\gamma)y_t^M(0,z)-y_t^T(z)] \tag{19}$$

where,

$$y^T(z)=z\left(\frac{\eta}{R}\right)^{\frac{\eta}{1-\eta}}, \quad y^M(0,z)=zvA^M\left(\frac{vA^M\eta}{R}\right)^{\frac{\eta}{1-\eta}} \quad \text{and} \tag{20}$$

$$y^M(1,z)=\begin{cases} zA^M\left(\frac{A^M\eta}{2R+1-v}\right)^{\frac{\eta}{1-\eta}} & : v\le v^\star(R) \\ z\left[vA^M\left(\frac{vA^M\eta}{R}\right)^{\frac{\eta}{1-\eta}}+(1-v)\left(\frac{(1-v)\eta A^M}{R+1-v_a}\right)^{\frac{\eta}{1-\eta}}\right] & : v>v^\star(R). \end{cases} \tag{21}$$

Substituting equations (20) - (21) into equation (19) shows that $E(\pi^M(z))-\pi^T(z)$ is increasing in z, since, by assumption, $A^M>\left[(1-\gamma)v^{1/(1-\eta)}\right]^{-1/(1-\eta)}$.

Proof of Proposition 2: The household's first order condition for capital implies that the steady-state rental rate is:

$$R=\frac{1}{\beta}+\delta-1, \tag{22}$$

and hence the steady-state price of capital does not depend on the probability of grid power. It follows that an increase in v does not affect profits for a traditional firm. Therefore, we only need to show that expected profits for a potential modern entrant with a given z are increasing in v. By the envelope theorem:

$$\frac{\partial E(\pi^M(z))}{\partial v} = \gamma[y_1^M(1,z) - y_0^M(1,z) + f_0(1,z)] + (1-\gamma)y_1^M(0,z). \tag{23}$$

Note that the expectation is taken over x, the indicator variable which determines if the firm has generator access. If $v < v^\star$, then firms with generator access operate at full capacity when the power is off, implying that $y_0^M(1,z) = y_1^M(1,z)$. When $v > v^\star$, $y_1^M(1,z) > y_0^M(1,z)$. In either case, equation (23) is positive, implying that $E(\pi^M(z))$ is increasing in v. □

Proof of Proposition 3: We define steady state A to be the steady state of the economy when the probability of grid power is $v_a < 1$. We use this steady state as a baseline from which to calculate the short-run partial-equilibrium and long-run general-equilibrium effects of eliminating outages. The first order conditions from the traditional firm's profit maximization problem imply that capital demand for a traditional firm with productivity, z in steady state A equals:

$$k_a^T(z) = z\left(\frac{\eta}{R}\right)^{\frac{1}{1-\eta}}. \tag{24}$$

Similarly, the first order conditions from the modern firm's profit maximization problem imply that productive capital demand for a modern firm with generator access $x \in \{0,1\}$ and productivity z in steady state A equals:

$$k_a^M(0,z) = z\left(\frac{v_a \eta A^M}{R}\right)^{\frac{1}{1-\eta}} \quad \text{and} \quad k_a^M(1,z) = \begin{cases} z\left(\frac{\eta A^M}{2R+1-v_a}\right)^{\frac{1}{1-\eta}} & : v_a \leq v^\star(R) \\ z\left(\frac{v_a \eta A^M}{R}\right)^{\frac{1}{1-\eta}} & : v_a > v^\star(R). \end{cases} \tag{25}$$

Demand for generator capital by a modern firm with generator access and productivity z equals:

$$k_a^S(1,z) = \begin{cases} z\left(\frac{\eta A^M}{2R+1-v_a}\right)^{\frac{1}{1-\eta}} & : v_a \leq v^\star(R) \\ z\left(\frac{(1-v_a)\eta A^M}{R+1-v_a}\right)^{\frac{1}{1-\eta}} & : v_a > v^\star(R). \end{cases} \tag{26}$$

Let $z_a^\star$ denote the equilibrium productivity cutoff in steady state A. To calculate aggregate output, we substitute the above expressions for capital demand in each sector into the respective production functions (equations (1) and (2)) and integrate over the distribution of entrepreneurs. Aggregate output in the traditional, Y_a^T, and modern, Y_a^M, sectors equals:

$$Y_a^T = \left(\frac{\eta}{R}\right)^{\frac{\eta}{1-\eta}} \int_1^{z_a^\star} z\,dG(z) \quad \text{and} \tag{27}$$

$$Y_a^M = \begin{cases} \left[\gamma A^M \left(\frac{A^M \eta}{2R+1-v_a}\right)^{\frac{\eta}{1-\eta}} + (1-\gamma) v_a A^M \left(\frac{v_a \eta A^M}{R}\right)^{\frac{\eta}{1-\eta}}\right] \int_{z_a^\star}^{\infty} z\,dG(z) & : v_a \leq v^\star(R) \\ \\ \left[v_a A^M \left(\frac{v_a A^M \eta}{R}\right)^{\frac{\eta}{1-\eta}} + \gamma (1-v_a) A^M \left(\frac{(1-v_a)\eta A^M}{R+1-v_a}\right)^{\frac{\eta}{1-\eta}}\right] \int_{z_a^\star}^{\infty} z\,dG(z) & : v_a > v^\star(R). \end{cases} \tag{28}$$

Aggregate output, Y_a, equals the sum of aggregate output in the traditional and modern sectors: $Y_a = Y_a^T + Y_a^M$.

We compute the short-run partial-equilibrium effect of eliminating outages. Define $\tilde{Y}$ to equal aggregate output when $v = 1$, but the productivity cutoff equals its value when $v = v_a$ ($z_a^\star$) and the demands for capital equal their values when $v = v_a$ (equations (24) - (26)):

$$\tilde{Y} = Y_a^T + \begin{cases} \left[\gamma A^M \left(\frac{A^M \eta}{2R+1-v_a}\right)^{\frac{\eta}{1-\eta}} + (1-\gamma) A^M \left(\frac{v_a \eta A^M}{R}\right)^{\frac{\eta}{1-\eta}}\right] \int_{z_a^\star}^{\infty} z\,dG(z) & : v_a \leq v^\star(R) \\ \left[A^M \left(\frac{v_a A^M \eta}{R}\right)^{\frac{\eta}{1-\eta}}\right] \int_{z_a^\star}^{\infty} z\,dG(z) & : v_a > v^\star(R). \end{cases} \tag{29}$$

The short-run partial-equilibrium effect of eliminating outages equals $\tilde{Y} - Y_a$. This represents the difference between output when firms choose their scale and sector but experience no outages ex-post and actual output.

To compute the long-run general-equilibrium effect of eliminating outages, we define steady state B to be the steady state of the economy when $v = 1$. Let $z_b^\star$ be the equilibrium productivity cutoff in steady state B. Aggregate output in the traditional and modern sectors in steady state B equals:

$$Y_b^T = \left(\frac{\eta}{R}\right)^{\frac{\eta}{1-\eta}} \int_1^{z_b^\star} z\,dG(z) \quad \text{and} \quad Y_b^M = A^M \left(\frac{A^M \eta}{R}\right)^{\frac{\eta}{1-\eta}} \int_{z_b^\star}^{\infty} z\,dG(z).$$

Aggregate output in steady state B equals $Y_b = Y_b^T + Y_b^M$. The long-run general-equilibrium effect of eliminating outages equals $Y_b - Y_a$. This represents the difference between output in the steady state with no outages and output in the steady state with outages when the probability of grid power equals ν_a.

To demonstrate that the long-run general-equilibrium effect of eliminating outages exceeds the short-run partial-equilibrium effect, we must show that $Y_b - Y_a > \tilde{Y} - Y_a$. First, note that by Proposition 2, the productivity cutoff in steady state B is less than the productivity cutoff in steady state A: $z_b^\star < z_a^\star$. Then, since $A^M > \left[(1-\gamma)\nu^{1/(1-\eta)}\right]^{-1/(1-\eta)} > 1$, it follows that:

$$Y_b > \left(\frac{\eta}{R}\right)^{\frac{\eta}{1-\eta}} \int_1^{z_a^\star} z\, dG(z) + A^M \left(\frac{A^M \eta}{R}\right)^{\frac{\eta}{1-\eta}} \int_{z_a^\star}^{\infty} z\, dG(z). \tag{30}$$

We show that the right-hand-side of equation (30) is larger than the value of $\tilde{Y}$ defined in equation (29). First, observe that the first term on the right-hand-side of equation (30) equals Y_a^T. Second, one can show that the second term on the right-hand-side of equation (30) always exceeds the second term in equation (29). Therefore, it follows that $Y_b > \tilde{Y}$ which implies that $Y_b - Y_a > \tilde{Y} - Y_a$. □

Definition of a competitive equilibrium: We define a sequence-of-markets equilibrium for this economy. We denote whether a modern firm has generator access with indicator variable $x \in \{0,1\}$, where $x = 1$ denotes generator access and $x = 0$ denotes no access. A *sequence-of-markets equilibrium* consists of: a sequence of rental rates of capital, $\{R_t\}_{t=0}^{\infty}$; productivity cutoffs, $\{z_t^\star\}_{t=0}^{\infty}$; household allocations, $\{C_t, K_t\}_{t=0}^{\infty}$; and entrepreneurial allocations $\{k_t^T(z), k_t^S(1,z), k_t^M(x,z), e_{1t}^G(x,z), f_{0t}(1,z)\}_{t=0}^{\infty}$ for all $x \in \{0,1\}$ and for all $z \in [1, \infty]$ such that:

1. Given prices, allocations of entrepreneurs across the traditional and modern sectors are consistent with the modern-sector productivity cutoffs, $\{z_t^\star\}_{t=0}^{\infty}$, defined in equation (**??**).

2. Given prices, traditional-sector allocations solve the profit maximization problem for all firms in the traditional sector and modern-sector allocations solve the profit maximization problem for all firms in the modern sector.

3. Given prices and firm profits, household allocations maximize (**??**) subject to the budget constraint:

$$C_t + K_{t+1} = R_t K_t + (1-\delta)K_t + \int_1^{z_t^\star} \pi_t^T(z)\, dG(z) + \int_{z_t^\star}^{\infty} (\gamma \pi_t^M(1,z) + (1-\gamma)\pi_t^M(0,z) - \Omega)\, dG(z)$$

and the non-negativity constraints, $C_t \geq 0$, and $K_t \geq 0$, where $\pi_t^T(z)$ are the profits of the traditional firms with productivity z, $\pi_t^M(x,z)$ are the profits of the modern firms with generator access, x, and productivity z.

4. The market for capital clears:

$$K_t = \int_1^{z_t^\star} k_t^T(z)dG(z) + \int_{z_t^\star}^{\infty} (\gamma k_t^M(1,z) + (1-\gamma)k_t^M(0,z) + \gamma k_t^S(1,z))dG(z). \tag{31}$$

We are interested primarily in how eliminating outages effects the economy in the long-run. For this it is useful to define a *steady state competitive equilibrium*, which consists of a constant rental rate, R; productivity cutoff $z^\star$; household allocations, $\{C,K\}$; and entrepreneurial allocations $\{k^T(z), k^S(1,z), k^M(x,z), e_1^G(x,z), f_0(1,z)\}$ for all $x \in \{0,1\}$ and for all $z \in [1,\infty]$ such that conditions (1)-(4) hold and all variables are constant from one period to the next.

B. Quantitative Version of the Model

Definition of a competitive equilibrium. We define a *sequence-of-markets* equilibrium for this economy as sequences of prices $\{W_t, R_t\}_{t=0}^{\infty}$, grid-power probabilities, $\{\nu_t\}_{t=0}^{\infty}$, fraction of entrepreneurs with political connectedness q and managerial ability z in the traditional sector, $J^T(q,z)$, in the modern sector without generator access, $J^{M,N}(q,z)$ and in the modern sector with generator access, $J^{M,S}(q,z)$, allocations for the households $\{C_t, K_{t+1}\}_{t=0}^{\infty}$ and allocations for firms with political connectedness q and managerial ability z:
$\{n_t^T(q,z), n_t^M(q,z), k_t^T(q,z), k_t^S(q,z), k_t^M(q,z), e_{1t}^G(q,z), f_{0t}(q,z)\}_{t=0}^{\infty}$ for all $z \in [1,\infty]$ and $q \in \{0,1\}$ such that:

1. Given prices, the fraction of entrepreneurs that operate the traditional technology, the modern technology without a generator and the modern technology with a generator satisfy the optimality condition defined in equation (9).

2. Given prices, traditional-sector allocations solve the profit maximization problem for all entrepreneurs in the traditional sector and modern-sector allocations solve the profit maximization problem for all entrepreneurs in the modern sector.

3. Given prices and entrepreneurial profits, household allocations maximize lifetime utility subject to the budget constraint:

$$\begin{aligned} C_t + K_{t+1} = {} & Q_t + W_t + R_t K_t + (1-\delta)K_t \\ & + \int_1^{\infty} \left[\pi_t^T(0,z)J^T(0,z) + \pi_t^T(1,z)J^T(1,z)\right] dG(z) \\ & + \int_1^{\infty} \left[(\pi_t^{M,N}(0,z) - A\Omega)J^{M,N}(0,z) + (\pi_t^{M,N}(1,z) - A\Omega)J^{M,N}(1,z)\right] dG(z) \\ & + \int_1^{\infty} \left[(\pi_t^{M,S}(0,z) - A\Omega)J^{M,S}(0,z) + (\pi_t^{M,S}(1,z) - A\Omega)J^{M,S}(1,z)\right] dG(z) \end{aligned} \tag{32}$$

   and the non-negativity constraints, $C_t \geq 0$, and $K_t \geq 0$.

4. The markets for capital and labor clear:

$$
\begin{aligned}
K_t = & \int_1^{\infty} \left[k_t^T(0,z)J^T(0,z) + k^{M,N}(0,z)J^{M,N}(0,z) + k^{M,S}(0,z)J^{M,S}(0,z)\right] dG(z) \\
& + \int_1^{\infty} \left[k_t^T(1,z)J^T(1,z) + k^{M,N}(1,z)J^{M,N}(1,z) + k^{M,S}(1,z)J^{M,S}(1,z)\right] dG(z) \\
& + K^G
\end{aligned} \tag{33}
$$

$$
\begin{aligned}
N_t = & \int_1^{\infty} \left[n_t^T(0,z)J^T(0,z) + n^{M,N}(0,z)J^{M,N}(0,z) + n^{M,S}(0,z)J^{M,S}(0,z)\right] dG(z) \\
& + \int_1^{\infty} \left[n_t^T(1,z)J^T(1,z) + n^{M,N}(1,z)J^{M,N}(1,z) + n^{M,S}(1,z)J^{M,S}(1,z)\right] dG(z)
\end{aligned} \tag{34}
$$

5. The probability of grid power is such that the rationed grid-electricity demand equals the supply (equation (13)).

C. Calibration

Table C.1 reports the model and empirical values of the moments used for the baseline calibration. Table C.2 reports the effect of a one percent increase in each parameter on the values of each of the eight moments. We order the table so that the parameter's primary moments are on and near the diagonal of the matrix. In all cases, changes in the parameter values meaningfully affect the parameter's primary moments.

Table C.1: Model Fit

Moment	Model	Target
(variable cost of self-generation)/(grid-electricity price)	4.33	4.33
(average cost of self-generation)/(grid-electricity price)	5.51	5.51
Fraction of self-generated electricity	0.59	0.59
Modern electricity share	0.07	0.07
Fraction of modern labor	0.63	0.63
Fraction of modern entrepreneurs	0.30	0.30
Fraction of modern entrepreneurs with a generator	0.82	0.82
Fraction of modern entrepreneurs without outages	0.20	0.20

Note: This table reports the empirical and model values of the moments used to calibrate the parameters in Table 2 for the baseline economy. We compute the modern electricity share in the model in a counterfactual steady state in which the probability of grid power equals 0.93.

Table C.2: Elasticities of Moments to Parameters

	$\frac{Ps}{Pg}$	Avg cost$\left(\frac{self}{grid}\right)$	$\frac{Self}{Grid}$	$\frac{Lm}{L}$	$\frac{Nm}{N}$	$\frac{Nm_{gen}}{Nm}$	$\frac{Nm_{q1}}{Nm}$	elec share
χ	-1.0	-0.8	0.3	0.4	0.4	0.1	-0.6	0.0
A_S	-1.0	-1.0	0.4	0.6	0.6	0.2	-0.7	0.4
P_g	-1.0	-1.0	-3.7	1.5	1.4	0.3	-2.1	0.0
λ	0.0	0.0	-0.4	-0.3	0.0	0.0	0.2	0.0
Ω	0.0	0.0	-0.5	-0.2	-1.0	0.1	0.6	0.0
ζ	0.0	0.0	0.1	0.1	0.8	-0.3	-0.8	0.0
ρ	0.0	0.0	0.6	-0.1	-0.1	-0.1	1.2	0.0
μ	0.0	0.0	-0.7	1.3	1.1	0.3	-1.3	-0.8

Note: Each row reports the percent change in the eight moments (from their values in the baseline calibration) from a one percent increase in the parameter value. The primary moments that discipline each parameter are on or near the diagonal of the matrix.

We re-calibrate P^G, χ, A^S, A^T, ζ, and ρ for each country in our study. We discipline ζ to match the country-specific fraction of modern firms that experience outages that have access to a generator. We pin down ρ to match the country-specific fraction of modern firms that report zero outages. We choose χ and A^S for each country to match the ratios of the average and marginal cost of self-generated electricity relative to grid electricity. We choose the regulated grid-electricity price in each country, P^G, to match the country-specific fraction of electricity that firms with generators produce themselves. We determine the country-specific values of A^T to match the ratio of output per worker in the specific country relative to its value in Nigeria. Table C.3 reports the values of these country-specific targets and Table C.4 reports calibrated parameter values. The calibrated model in each country matches the corresponding targets out to four decimal places. We describe the data sources and the construction of these targets below.

Table C.3: Country Specific Targets

Country	$\text{AC}^{self}/\text{AC}^{grid}$	$\text{MC}^{self}/\text{MC}^{grid}$	E^s/E	Y/Y_{NGA}	$N_{m,q=1}/N_m$	$N_{m,gen}/N_{m,q=0}$
Ghana	3.66	3.00	0.21	0.90	0.06	0.75
Nigeria	5.51	4.33	0.59	1.00	0.20	0.82
Tanzania	3.22	2.70	0.28	0.38	0.13	0.52
Uganda	2.48	2.05	0.21	0.32	0.24	0.80

Note: This table reports the empirical values of the country-specific targets for each of the four countries in our study. The targets are: (1) the average cost of self-generated electricity relative to grid electricity, (2) the marginal cost of self-generated electricity relative to grid electricity, (3) self-generated electricity relative to total electricity (4) output per worker in the specific country relative to output per worker in Nigeria (5) fraction of modern entrepreneurs that do not experience outages and (6) the fraction of modern entrepreneurs that experience outages that have a generator.

Table C.4: Country Specific Parameters

Country	Price of grid electricity: P^G	Self-gen Leontief: χ	Self-gen TFP: A^S	Trad. TFP: A^T	Gumbel variance: ζ	Fraction with no outages: ρ
Ghana	0.12	1.75	1.52	0.87	0.25	0.04
Nigeria	0.11	2.14	1.02	1.00	0.24	0.08
Tanzania	0.11	1.51	2.28	0.49	1.61	0.13
Uganda	0.10	1.63	3.00	0.43	0.08	0.13

Note: This table reports the values of the country-specific parameters in the model.

We calculate the average and variable costs of self-generation in each country. All cross-country variation in these cost estimates comes from variation in diesel fuel prices; we assume that the capital and maintenance costs of self-generation are the same for all countries. We use estimates from the World Bank Technical Assessment (World Bank, 2007) to calculate the capital cost of a typical generator. The Technical Assessment reports that a 100 kW diesel generator would cost 760 dollars per kW, and last 20 years with a capacity factor of 0.8, (World Bank, 2007). Using an interest rate of 10 percent implies that the annual capital-cost per kWh equals 1.3 cents. The maintenance cost is 5.9 cents per kWh (World Bank, 2007).

We calculate the variable cost of self-generated electricity for the 100 kilowatt diesel generator with 30 percent efficiency. We use the 2014 price of diesel fuel in each country from the World Development Indicators. To convert dollars per liter of diesel fuel into dollars per kWh, we convert liters of diesel fuel into BTUs, and then convert BTUs into kWhs, adjusting for the 30 percent efficiency of the generator.

The average cost per kWh equals the sum of the capital, maintenance and variable costs per kWh. We use a capacity factor of 0.8 when we construct the average cost ratio in the model to ensure that it is consistent with the data. Table C.5 reports the average price per liter of diesel fuel and the variable and average costs of self-generated electricity in each country.

Table C.5: Self-Generation Costs

Country	Diesel Price ($/ltr)	Variable cost ($/kWh)	Average cost ($/kWh)
Ghana	1.03	0.32	0.40
Nigeria	0.84	0.26	0.34
Tanzania	1.20	0.38	0.45
Uganda	1.11	0.35	0.42

Note: This first column of this table reports the the price of diesel fuel in 2014 from the World Development Indicators. The second and third columns report the authors' calculations of the variable and average cost of self-generated electricity. All values are in year 2014 dollars.

We use the micro data from the World Enterprise Surveys to compute the following targets in each country: (1) the fraction of modern firms that experience outages that have access to a generator, (2) the fraction of electricity firms with a generator generate themselves, and (3) the fraction of modern firms that do not experience outages. We drop all observations for which the firm size is less than 10. The reported targets in each country are the mean values from the WES.

To calibrate TFP in each country, we compare output per worker in the specific country to output-per worker in Nigeria. Data on output per worker is from the Penn World Tables. We use output per worker in each country in the same year as the World Bank Enterprise Survey for that country, reported in Table C.6.

Table C.6: Year of the World Enterprise Survey

Country	Enterprise Survey Year
Ghana	2013
Nigeria	2014
Tanzania	2013
Uganda	2013

Note: This table reports the year of the enterprise survey in each country.

The baseline calibration uses measures of size of the modern sector from the 2017 Nigerian National Survey of Micro, Small, and Medium Enterprises (SMEDA, 2017). The survey includes a representative sample of micro enterprises (those with less than 10 employees) and small (between 10 and 49 employees) and medium enterprises (between 50 and 199 employees). There is no information on large enterprises (those with greater than 199 employees). The survey has two modules: (1) the micro enterprises are covered in the National Integrated Survey of Households and (2) the small and medium enterprises are covered in National Integrated Survey of Establishments. The survey covers all major sectors of the Nigerian economy, all geographic areas, and includes both formal and informal firms. We do not have access to the raw data from the survey. We take all information from the report, (SMEDA, 2017), assembled by the Small and Medium Enterprises Development Agency of Nigeria. The report compiles two sets of aggregate statistics, one set for micro enterprises and the second set for small and medium enterprises.

We use the survey results to compute the fraction of firms and workers that use electricity. The survey reports the average number of hours an enterprise operates with an alternative source of power. Firms that report zero use of alternative power "have little-to-nil need for [any] power supply" (SMEDA (2017), page 33). Since these firms do not use electricity in the production process, they correspond to the traditional sector in our model. Using this definition, approximately 70 percent of micro enterprises are traditional and 6 percent of small and medium enterprises are traditional. To calculate the fraction of traditional enterprises relative to total enterprises, we divide the number of traditional enterprises by the total number of micro, small, and medium enterprises. This calculation assumes that the number of large enterprises equals zero. Micro enterprises are so prevalent that any reasonable assumption about the number of large enterprises does not have meaningful effects on the fraction of traditional enterprises. In particular, micro, small and medium enterprises account for 76.5 percent of total employment in the Nigerian economy, implying that large enterprises employ at most 183,232,27 people. Since each large enterprise must employ 200 or more people, there can be at most $183{,}232{,}27/200 = 91{,}616$ large enterprises. If we assume that there are 91,616 large enterprises, instead of zero, and all large enterprises are modern, then the fraction of traditional enterprises decreases from 0.703 to 0.701.

We calculate the fraction of total workers that are traditional. Approximately, 76.5 percent of the workers in Nigeria are employed by micro, small, and medium enterprises (SMEDA, 2017). We assume that the remaining 23.5 percent of workers are employed by large firms in the modern sector. To divide the workers at micro, small and medium enterprises into the traditional and modern sectors, we need information on how firm-size varies between the modern and the traditional firms. While this information is not available in the Nigerian survey, we use the fact that 70.4 percent of micro enterprises and 6 percent of small and medium enterprises are traditional, and we assume that each traditional micro enterprise employs one person and each traditional small and medium enterprise employs 10 people.

We use the US GDP deflator to convert all monetary values to 2014 dollars.

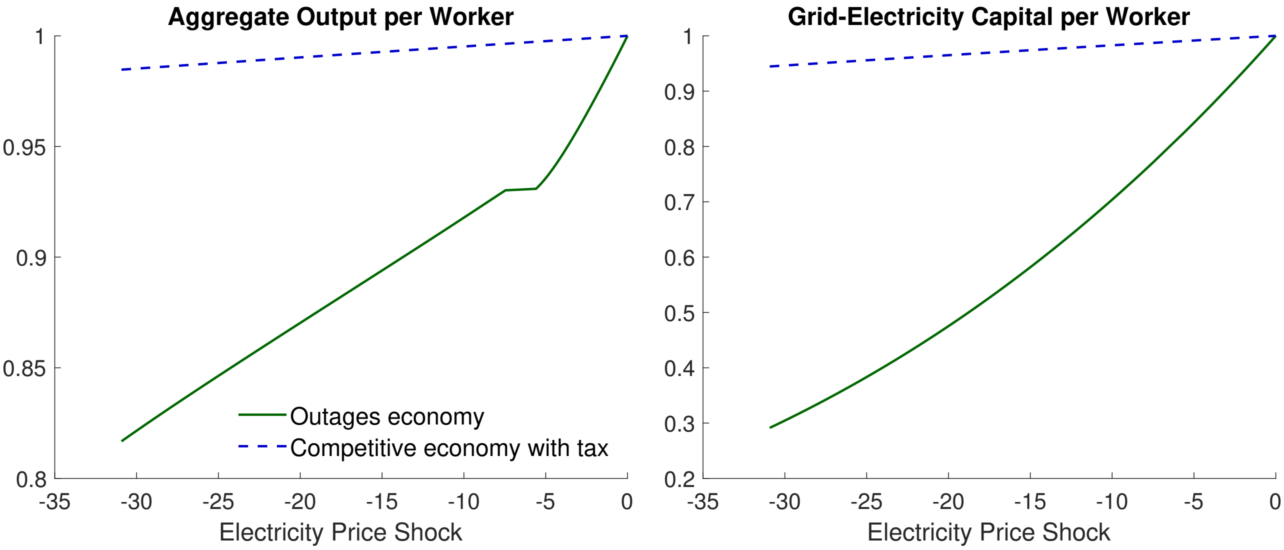
D. Additional Results From the Quantitative Model

Table D.1: Equilibrium Values of Macro-Aggregates in the Initial Steady State

	Ghana	Nigeria	Tanzania	Uganda
Grid-electricity price: P^G	0.12	0.11	0.11	0.10
Grid-electricity capital: K^G	0.60	0.35	0.37	0.29
Grid-electricity supply: E^G	0.70	0.48	0.50	0.42
Fraction of modern labor: N^M	0.78	0.62	0.74	0.61
Fraction of modern entrepreneurs: Q^M	0.41	0.30	0.64	0.23
Probability of grid power: ν	0.79	0.41	0.72	0.79

Note: This table reports the equilibrium values of a number of variables in the initial steady state in each country. While the units of the grid-electricity price, capital, and supply are not meaningful independent of the model, the comparison of the different values across countries is meaningful.

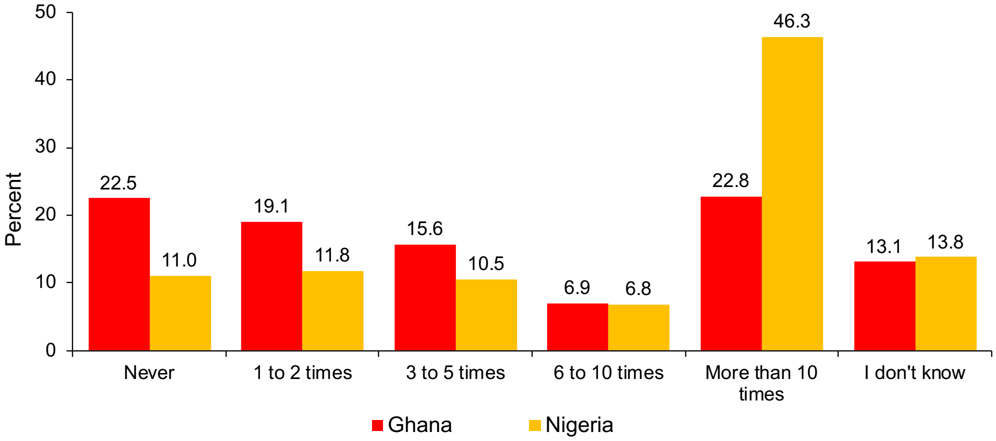
Figure D.1: Competitive Economy With a Tax versus Outages Economy



Note: This figure plots the responses of output per worker and grid-electricity capital per worker in Nigeria to an electricity price shock in our outages economy (solid green line) and in a competitive economy with a tax (dashed blue line). The right-most point on the solid green line in both panels corresponds to the counterfactual no-outages steady state for Nigeria and the left-most point corresponds to the initial steady state. Moving from right to left along the outages-economy (solid green) line, we reduce the price of grid-electricity by the amount on the x-axis. Moving from right to left along the dashed blue line, we introduce a tax on electricity suppliers, that would reduce the price electricity suppliers receive by the amount on the x-axis if electricity prices could not adjust.

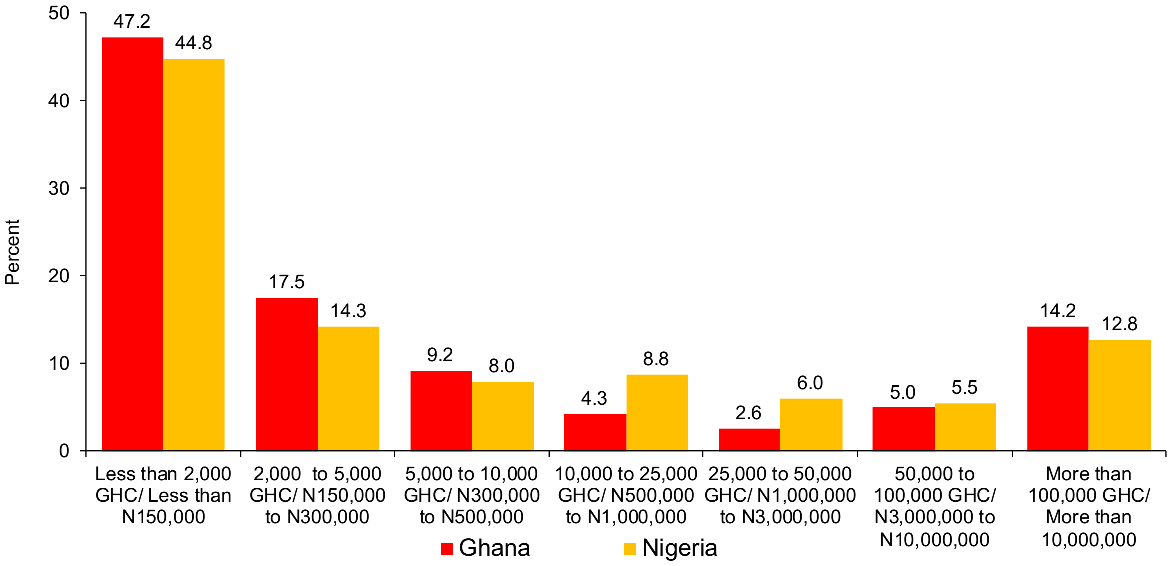
E. Additional Survey Results

Figure E.1: Frequency of Power Outages of Surveyed Firms



Note: This figure reports the frequency of power outages in the previous year among the surveyed firms in Ghana (red) and Nigeria (yellow).

Figure E.2: Average Monthly Revenues of Surveyed Firms



Note: This figure reports the average monthly revenues among the surveyed firms in Ghana (red) and Nigeria (yellow).