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Lifelines: The Resilient Infrastructure Opportunity

Background Paper

Underutilized Potential

The Business Costs of Unreliable Infrastructure in Developing Countries

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Abstract

This study constructs a microdata set of about 143,000 firms to estimate the monetary costs of infrastructure disruptions in 137 low- and middle-income countries, representing 78 percent of the world population and 80 percent of the GDP of low- and -middle-income countries. Specifically, this study assesses the impact of transport, electricity, and water disruptions on the capacity utilization rates of firms. The estimates suggest that utilization losses amount to $151 billion a year—of which $107 billion are due to transport disruptions, $38 billion due to blackouts, and $6 billion due to dryouts. Moreover, this study shows that electricity outages are causing sales losses equivalent to $82 billion a year. Firms are also incurring the costs of self-generated electricity, estimated to amount to $64 billion a year (including annualized capital expenditure). At almost $300 billion a year, these figures highlight the substantial drag that unreliable infrastructure imposes on firms in developing countries. Yet, these figures are likely to be under-estimates as neither all countries nor all types of impacts are covered.

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Produced by the Research Support Team

Underutilized potential:
The business costs of unreliable infrastructure in developing countries

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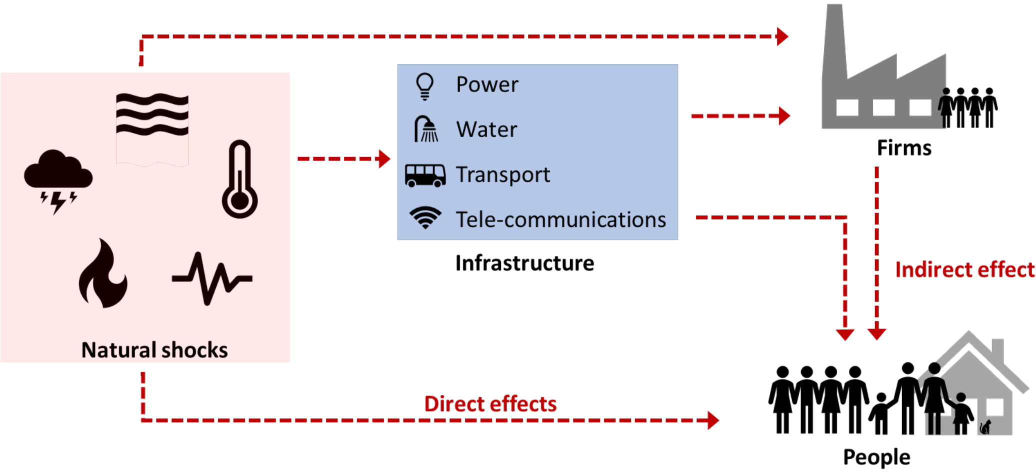
1. Introduction

From serving our most basic needs to enabling our most ambitious ventures in trade or technology – infrastructure services underpin all our efforts in supporting our wellbeing and development. Reliable water, sanitation, and energy services and efficient transport infrastructure are universally accepted to be essential for making progress in raising the quality of life of people. By one estimate, governments in low and middle income countries around the world are investing around US$ 1 trillion (or between 3.4% to 5% of GDP) in infrastructure (Fay et al., 2019). Still, despite substantial investment volumes, the quality and adequacy of infrastructure services varies widely across countries.

Still, despite substantial investment volumes, the quality and adequacy of infrastructure services varies widely across countries. The experience of millions of people around the world shows that simply being connected to infrastructure networks does not guarantee reliable services. Especially the fast-growing cities in developing countries are facing the challenging consequences of substandard infrastructure, often at a significant cost. Aging equipment, underfunding, poor maintenance, and rapid expansion are some of the key factors resulting in unreliable electricity grids, water and sanitation systems, and overstrained transport networks. In addition, natural hazards are often a leading cause of disruptions in these already fragile systems (Rentschler, Obolensky, & Kornejew, 2019).

Especially in developing countries, infrastructure systems continue to provide unreliable services and be vulnerable to external shocks, including natural hazards. In Dar es Salaam, Tanzania, frequent urban flooding is not only affecting households by destroying their assets and increasing the risk of water-borne diseases associated with a lack of adequate sanitation systems. In addition, flooding often disrupts the entire urban economy, even beyond the directly affected flood zones. As roads are flooded, public transport and all traffic come to a near standstill. People are unable to reach their work places, supply chains are interrupted, deliveries missed, and sales lost. Electricity supply is often affected too, resulting in power outages and thus halted economic activity. The regularity of these incidents mean that firms invest in expensive coping measures, ranging from the purchase of water tanks and diesel generators, to keeping expensive back-up inventories and contracting back-up suppliers. Overall, the lack of effective drainage systems and reliable transport and electricity systems is a defining factor of the urban economy, influencing the investment and risk-taking behaviors of all.

Figure 1 The extent to which natural shocks affect people depends on the resilience of infrastructure systems and the indirect impacts through firms



Unreliable infrastructure systems affect firms through various impact channels, which fall into three categories (Table 1). Most visible are the direct impacts: a firm relying on water to cool a machine cannot manufacture a product during a dryout; likewise, a restaurant with an electric stove cannot cook meals without power. Infrastructure disruptions interrupt firms' activities, force them to operate at less than full production capacity, reduce their sales, and cause delays in the supply and delivery of goods.

The indirect impacts of unreliable infrastructure are less immediate. They affect firms' investment decisions, influence what products can and cannot be produced, and influence the composition and innovativeness of an industry. For example, a firm is less likely to upgrade its machinery to more productive technology if blackouts force it to revert to manual production regularly. In the aggregate, these effects are visible in an economy's ability to generate wealth and in its international competitiveness.

Finally, in addition to direct and indirect impacts, firms incur costs for coping with unreliable infrastructure. A backup power generator, for example, reduces the direct impacts of blackouts but has high operating costs and requires an upfront purchase that prohibits more productive investments.

This study constructs a micro dataset of over 143,000 firms from the World Bank's Enterprise Surveys, and estimates the monetary costs of infrastructure disruptions. This data set covers an unprecedented 137 countries, representing 78 percent of the world's population and 80 percent of the GDP of low- and middle-income countries. The analysis estimates that utilization rate losses due to power, water, and transport disruptions amount to $151 billion a year, sales losses from electricity outages to $82 billion a year, and the additional costs of self-generating electricity to $65 billion a year. At a total cost of nearly $300 billion a year, these figures highlight the significance of unreliable infrastructure. In fact these numbers are likely to be lower-bound estimates of the global costs of outages because neither all countries nor all impact channels are covered by this analysis.

Table 1 Disrupted infrastructure services have multiple impacts on firms. Highlighted are the impact channels for which original estimates are presented in this study.

	Direct impacts	**Coping costs**	**Indirect impacts**
Power	• Interrupted activity • **Reduced utilization rates ($38 billion a year)** • **Sales losses ($82 billion a year)**	• **Generator investment ($6 billion a year)** • **Generator operational costs ($59 billion a year)** • Opportunity cost of alternative productive investments (such as in new machinery)	• Higher operational costs, creating barriers to market entry • Reduced competition due to lack of small and new firms • Reduced innovation • Inefficient sectoral allocation • Bias toward labor-intensive production • Inability to provide on-demand services and goods • Higher operational costs passed on to consumers and employees • Diminished competitiveness in international markets
Water	• Interrupted activity • **Reduced utilization rates ($6 billion a year)** • Sales losses	• Investment in alternative water sources (reservoirs, wells)	
Transport	• Interrupted activity • **Reduced utilization rates ($107 billion a year)** • Sales losses • Delayed supplies and deliveries	• Increased inventory • Expensive location choices in proximity to clients, ports, etc.	
Telecommunications	• Interrupted activity • Reduced utilization rates • Sales losses	• Expensive location choices in proximity to fast Internet service	

But access to infrastructure systems is insufficient if their unreliability hinders production and reduces output. In Africa, studies at the firm- and the country-level illustrate the severe consequences of disrupted electricity infrastructure: increasing the frequency of power outages by one percent is estimated to decrease firm output by 3.3 percent in the short run and reduce GDP per capita by 2.9 percent in the long run (Andersen & Dalgaard, 2013; Mensah, 2018). Similarly, disruptions to the water supply and congestion in transportation infrastructure have been shown to decrease economic output (Iimi, 2011; Islam & Hyland, 2018; Sweet, 2011, 2013; World Bank, 2013).

In addition to such direct impacts, unreliable infrastructure also alters firms' incentives and industry dynamics. Some of these indirect effects are noticeable in firm productivity: In 23 African countries, a one percent increase in electricity outages would account for a loss in firms' total factor productivity of 3.5%, on average (Mensah, 2018). While the underlying dynamics are complex, some factors have been shown to be important. Infrastructure disruptions have a more severe impact on small firms with lower coping capacities, which limits entrepreneurship and reduces competition (Alby, Dethier, & Straub, 2013; Mensah, 2018; Poczter, 2017). Furthermore, unreliable infrastructure reduces the production technologies and industries that a country can host and thus diminishes its international competitiveness (World Bank, 2019). Such dynamics are felt by the population through reduced employment and increased costs for consumers (Mensah, 2018; Rentschler & Kornejew, 2017).

Firms that are affected by infrastructure disruptions can take adaptation measures to minimize the impact on their operations. Without the acknowledgement of the costs of such measures, the full effect of unreliable infrastructure cannot be understood. To deal with power outages, many firms in developing countries invest in diesel-powered back-up generators which, of course, are much more expensive to operate than drawing energy from a public grid (Farquharson, Jaramillo, & Samaras, 2018; Steinbuks & Foster, 2010). Ownership of generators is also linked to lower long-term productivity due to higher marginal costs that limit investments into other input factors (Mensah, 2016). Furthermore, backup generation using diesel generators significantly increases emissions of air pollutants such as PM2.5 and greenhouse gases like CO2, thus causing indirect costs in the form of health impacts or climate change (Farquharson et al., 2018; World Bank, 2018).

Adaptation to unreliable water infrastructure can be similarly costly, with potential coping measures including investments into reusability and conservation of water as well as the construction of wells accessing underground, river, or lake water (Kajitani & Tatano, 2009; Rose & Krausmann, 2013). Turning to transportation, firms have been shown to increase their inventories to keep up production despite delayed inputs. This, however, leads to higher costs of storage, opportunity costs of bound capital, and possible depreciation of stored goods (Guasch & Kogan, 2003; Iimi, Humphrey, & Melibaeva, 2015). Unreliable infrastructure also influences firms' location decisions, forcing them to compromise on other factors in order to avoid areas with low-quality infrastructure (Arauzo-Carod, Liviano-Solis, & Manjón-Antolín, 2010; Kim & Cho, 2017).

2. Unreliable and fragile infrastructure is affecting economies around the world

Disruption of infrastructure services affect firms in every economy around the world. However, disruption frequencies vary widely across as well as within economies. Whether or not a firm will have to cope with blackouts, water shortages, logistical obstacles or loss of tele communication ultimately depends on the interaction of country-level as well as firm-level exposure and resilience factors. Such factors include for example natural hazards, governance quality, production technology and back-up systems. This section records the prevalence of infrastructure disruptions and tries to identify country- and firm-specific exposure and resilience factors.

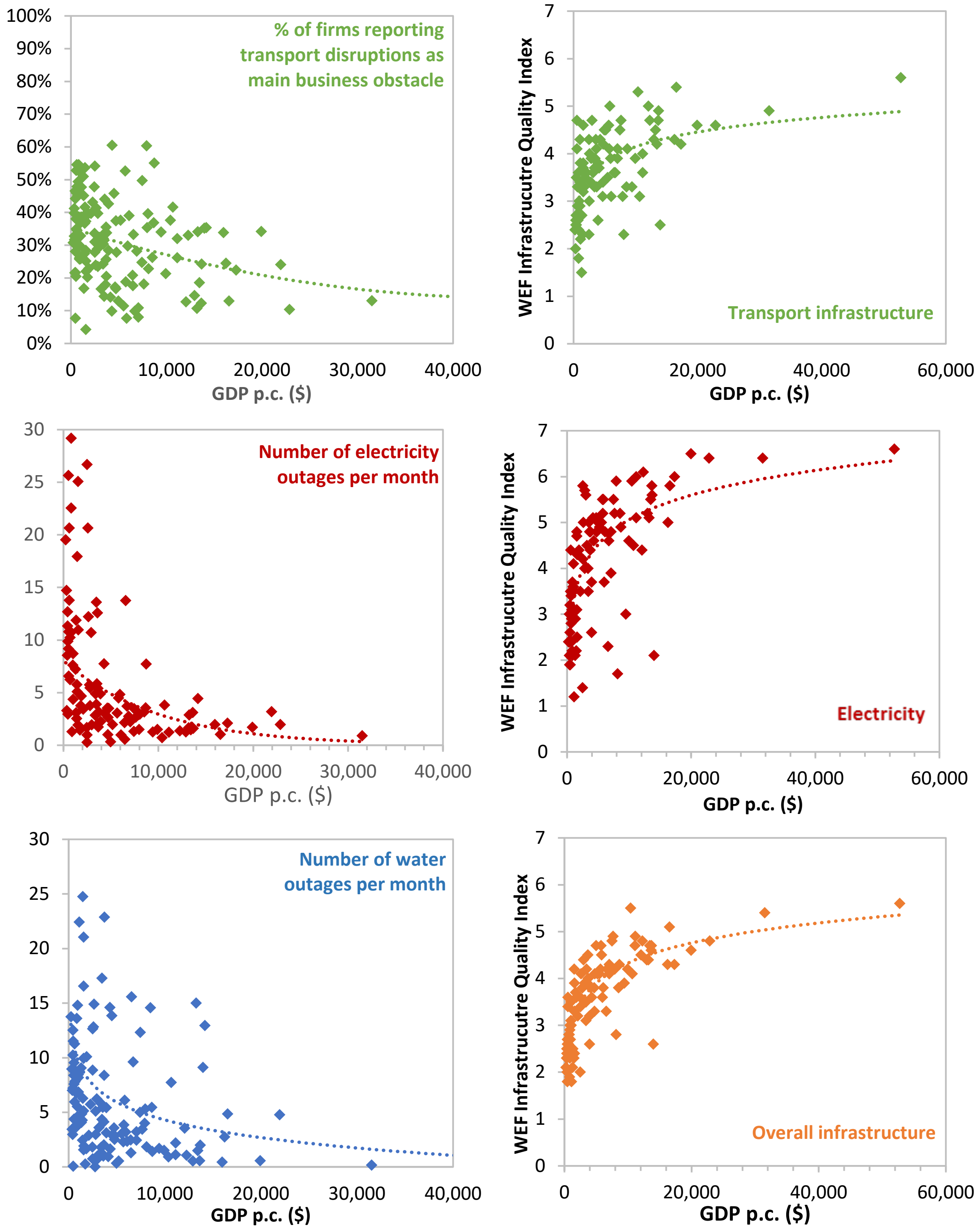
To better understand how firms are affected, it is useful to investigate whether certain firms are particularly likely to be affected by disruptions. Preliminary results suggest that infrastructure is a networked system, so that disruptions are experienced by – at least to some degree – all firms. Disruption prone firms seem to operate in all sectors, and possess costly back-up systems (e.g. generators). State or foreign owned firms tend to experience fewer disruptions. The location of firms can only explain certain disruption types (water and transport). Similar to vulnerability analyses for households, this section will explore what makes firms susceptible to experiencing disruptions and incurring high losses.

2.1. Country level evidence: Which countries experience the most disruptions?

The World Bank’s Enterprise Surveys enable a descriptive analysis of which countries experience the most disruptions to electricity, water, and transport infrastructure. This provides estimates for up to 139 low and middle-income countries, and can be complemented with (partially overlapping) data from the WEF for 96 middle and high-income countries.

Overall, the data portraits a consistent picture: there are substantial differences in the quality of infrastructure across countries. The disruption data from the World Bank’s Enterprise Surveys demonstrate this, and the infrastructure quality index by the World Economic Forum (WEF) confirms it. The quality of infrastructure is generally linked closely to the level of economic development, proxied in Figure 2 by GDP per capita. For transport, water, electricity, and infrastructure more generally, more developed countries tend to have fewer disruptions and higher perceived infrastructure reliability. However, the data also shows that there exist significant differences in infrastructure quality levels for countries at the same income level. For instance, Bhutan’s (GDP p.c. $2,500) reliability of electricity is comparable to many developing countries, while Nigeria ($2,476) ranks among the lowest in the whole sample. Many factors can drive these patterns, and the remainder of this section will discuss and explore these aspects.

Figure 2 Infrastructure quality and GDP. Left: Infrastructure disruption levels based on World Bank Enterprise Survery data. Right: Infrastructure quality index from the World Economic Forum Global Competitiveness index.



2.2. What are the characteristics of disruptions-prone firms?

Country-level factors are important for the individual firm. The empirical analysis of our firm-level data thus introduces country-specific controls common to all firms in corresponding economy alongside general country-level fixed effects. Country-level data on economic and demographic variables is sourced from the WDI and WGI databases. Climate data to measure natural risks has been extracted from the ERA5 climate re-analysis model (Copernicus Climate Change Service, 2018).[1]

While the impact of infrastructure disruptions is typically transmitted across wide networks, they are not felt by all firms in the same way. This section focuses on statistical properties of firm-level variables do identify correlates of disruptions to shed light on exposure and resilience factors. All firm-specific information is retrieved from the *Enterprise Surveys (ES).* All specifications include two-digit ISIC (revision 3.1) sector fixed effects to capture production technology-induced exposure and other sector-specific factors. Standard errors are clustered at the regional level to account for regressor correlation with region fixed effects and uncertainty about regressors' marginal effects being region-specific.

Table 2 summarizes the main empirical results. Specifically, it shows regressions of the full set of variables on i) the total annual duration of blackouts, ii) total annual duration of water supply disruptions or iii) a subjective index (1-4) of the severity of transport problems in overall business operation. Those three variables are directly or indirectly provided by the ES, while no similar information is given on telecommunication disruptions, unfortunately. Note that our global climate variables cover a selected set of geo coordinates, specifically up to three of the economically most important cities of each country. Thus, to reliably identify impacts of climate risks at the firm level (in particular extreme precipitation and storms), we restrict attention to firms in those cities, covering approximately a quarter of the full sample. Conclusions concerning non-climatic variables remain qualitatively unchanged in the full sample.

According to ISIC factor estimates, disruptions of **electricity** supply are significantly more prevalent within the mining sector, manufacturing of fabricated metal products as well as coke and petroleum refinement. By contrast, for air transport service providers, post and telecommunications as well as producers of telecommunication equipment, total annual blackout durations are significantly below average. This suggests that effective measures are taken to shield critical infrastructure to prevent outage-inflicted damage from spreading further. Moreover, larger and private firms tend to experience fewer outages while at the same time many outages cause firms to invest in own back-up generation. On the macro level, dynamism, high population density and growth is associated with more vulnerable electricity infrastructure while on the other hand outages and the business cycle are negatively related. Natural disasters do not seem to have a systematic impact on blackouts on the global level.

Water infrastructure disruptions tend to occur within the chemical industry, gastronomy and the production of food and beverages while wood and paper industries suffer significantly less water supply disruptions. As with electricity, larger firms experience less disruptions, while all other firm-level variables show no significance performance. On average, economies with higher urbanization are associated with fewer water supply irregularities. Concerning natural hazards, extreme precipitation and storms are

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[1] For a detailed description on how disaster risk variables have been constructed from hourly climate data, see appendix A.2.

positively associated with disruptions, while the metropolitan areas under investigation seem to be reasonably well protected against the consequences of drought.

When it comes to **transport** disruptions, mining, chemicals and manufacturing of electric and electronic devices face significantly more transport obstacles than the average firm. On the contrary, post and telecommunication, IT services, textiles and apparel production and gastronomy suffer from significantly fewer transportation problems. After controlling sector-specific effects, individual firms' exposure towards transport obstacles increases in age, size and frequency of storms. Further, they are positively correlated with generator ownership, possibly interpreted as a proxy of remoteness. By contrast, state ownership and effective (national) governance as measured by the WGI decrease transport problems. That exporters, conditional on sector affiliation, do not disproportionately complain about transportation problems suggests that effective coping strategies exist or that such obstacles tend to arise at the immediate, local level where they are harder to circumvent.

Table 2: Firm-level determinants of infrastructure disruptions

Dependent:	Blackouts	Water disruption	Transport problems
Firm age	-0.4731	0.8269	0.0033*
years since official registration	*(0.3981)*	*(0.6610)*	*(0.0019)*
Employment	-0.1362**	-0.0904*	0.0004*
number of full time employees	*(0.0613)*	*(0.0539)*	*(0.0002)*
State ownership	0.3797*	-0.3894	-0.0013*
% of total assets	*(0.2036)*	*(0.4195)*	*(0.0007)*
Export orientation	-0.2140	0.5570	-0.0031
% of total sales	*(3.7831)*	*(1.6675)*	*(0.0020)*
Generator ownership	130.1427***	21.7680	0.0829*
Dummy	*(34.1015)*	*(45.3034)*	*(0.0477)*
ISIC Sector Fixed Effects	YES	YES	YES
Output Gap	-35.7666**	1.8103	-0.0033
HP residual as % of HP trend	*(14.2614)*	*(4.2874)*	*(0.0213)*
GDP Growth	11.1562**	2.1227	-0.0030
annual, in %	*(5.5833)*	*(1.6454)*	*(0.0043)*
Electrification	-6.5491	15.1436**	0.0192
% of population	*(15.3368)*	*(6.9546)*	*(0.0116)*
Water access	16.9750	-2.9592	-0.0320
% of population	*(39.8634)*	*(16.1290)*	*(0.0265)*
Population	-4.4678	-1.2989	0.0003
in millions	*(3.0321)*	*(2.1559)*	*(0.0022)*
Population density	0.0000**	0.0000	0.0000
in 1/km^2	*(0.0000)*	*(0.0000)*	*(0.0000)*
Urbanisation	-37.1000	-80.5798***	0.0368
% of population	*(61.9500)*	*(14.6525)*	*(0.0472)*
WGI: Government Effectiveness	-196.1376	65.6708	-0.6385***
Index, standard normal	*(281.0073)*	*(103.7968)*	*(0.2137)*
Country Fixed Effects	YES	YES	YES
Droughts	-10.4036	3.0247	0.0053
0-100 % extreme precipitation shortfall	*(17.8841)*	*(6.9778)*	*(0.0370)*

Storms	8.8059	60.0757*	0.1052***
annual number of events	*(56.2382)*	*(33.4079)*	*(0.0392)*
Extreme rain	-0.0738	0.0437**	-0.0001
annual number of events	*(0.0605)*	*(0.0213)*	*(0.0001)*
N	20359	13734	23333
R^2	0.38	0.12	0.19

Estimated with weighted OLS, normalised survey stratification weights applied. Standard errors in parenthesis, clustered on region. Significance levels: *** 0.01, ** 0.05, * 0.10.

2.3. Firms' exposure to infrastructure disruptions vs. direct exposure to natural hazards

Based on Rentschler et al. (2019), this section investigates whether direct exposure to natural hazards influences firms' experience of infrastructure disruptions. In 13 African cities, no such link is found between exposure to flood hazards and unreliable infrastructure.

Especially developing countries tend to perform poorly in terms of the reliability and efficiency of their public infrastructure. Infrastructure users tend to experience frequent disruptions, such as power outages, water supply interruptions, or frequently occurring problems with transport networks. These disruptions can have a range of causes, ranging from sub-standard and malfunctioning equipment, poor management, lacking investment and maintenance, as well as natural stresses and disasters.

To analyze how natural shocks cause infrastructure disruptions, this analysis combines firm-level microdata and natural hazard exposure data. Enterprise Survey observations are used for 13 major African cities. Flood hazard data is drawn from the highest-quality flood map available in each city. Using the non-randomized ES locations, each firm's exposure is extracted using the local flood map. For the analysis, the flood exposure is then reclassified into the binary variable Flood-threatened that takes the value 1 if a firm is exposed to significant flood risk and 0 otherwise.

At the firm-level, there is no link between firms' flood exposure and experience of infrastructure disruptions. Table 3 displays the result from regressions on power outages, water disruptions, and transport problems in 13 African cities. The Flood-threatened dummy variable has no significant effect on the three types of disruption. The absence of a visible relationship between natural hazard exposure and infrastructure disruptions can be explained by two factors: other stressors and network effects.

Infrastructure disruptions are not only caused by natural hazards. Instead, a wide-range of other factors inhibit the functioning of infrastructure systems. Systems in developing countries are usually less robust and exhibit a wider range of vulnerabilities. Thus, the systems in the African cities analyzed here might be under greater relative pressure from other stressors that hides the influence of natural hazards (Rentschler et al., 2019).

Furthermore, infrastructure disruptions caused by natural hazards are likely to affect the whole system as infrastructure systems are large networks. The effects of a flood destroying power distribution infrastructure will not be limited to those firms located in the flood zone but will be felt by all firms in a city. Consequently, firm location is an insufficient proxy to pick up the true influence of natural disasters on infrastructure.

Table 3: The effect of flood-exposure on infrastructure disruptions as experienced by firms in 13 African cities

Dependent:	Blackouts	Water disruptions	Transport disruptions
Firm age	0.217	8.145**	-0.001
years of official registration	*(1.46)*	*(2.89)*	*(0.00)*
Employment	-0.912*	0.494	0.001
number of full time employees	*(0.50)*	*(0.90)*	*(0.00)*
State ownership	3.128	-0.656	0.015
in %	*(5.81)*	*(7.00)*	*(0.02)*
Export orientation	-0.214	4.232	-0.000
% of total sales	*(1.45)*	*(3.69)*	*(0.00)*
Generator ownership	69.452	126.011	0.054
Dummy	*(50.81)*	*(289.08)*	*(0.15)*
Distance to city centre	-0.001	0.008	-0.000
at the ward-level, in meter	*(0.00)*	*(0.01)*	*(0.00)*
ISIC Sector Fixed Effects	YES	YES	YES
City Fixed Effects	YES	YES	YES
Flood-threatened	28.583	54.883	0.150
Dummy	*(70.41)*	*(262.29)*	*(0.14)*
N	2217	828	2600
R^2	0.185	0.115	0.124

Results from weighted OLS regression, city-level normalized survey stratification weights applied. Standard errors in italics, clustered on cities. Significance levels: *** 0.01, ** 0.05, * 0.10

3. What are the business costs of infrastructure disruptions?

Reliable and efficient infrastructure systems are crucial to enable firms to follow long-term planning, and to maximize their capacity, without the need to invest excessively in expensive back-up or contingency technology. For instance, the ownership of costly diesel-based electricity generators is far less common in countries with reliable electricity supply. In addition, reliable and efficient infrastructure is key to facilitating firms' access to the markets and information that drive their ability to provide goods, services, and jobs. For as long as infrastructure systems remain disruption-prone, this will have substantial adverse effects on the continuity of production and service delivery, affecting the smooth functioning of supply chains, diminishing aggregate productivity, and restricting the ability of firms to trade and compete internationally.

This section assesses and quantifies the business cost of unreliable and vulnerable infrastructure. In the case of electricity outages, self-reported sales of firms are available through the World Bank's Enterprise Surveys (ES). This makes it possible to estimate directly the rate at which an additional hour of electricity outages reduces the sales of firms (Section 4.1). Similarly, self-reported electricity generation rates are used to assess the upfront and operating costs of self-generation (Section 4.2).

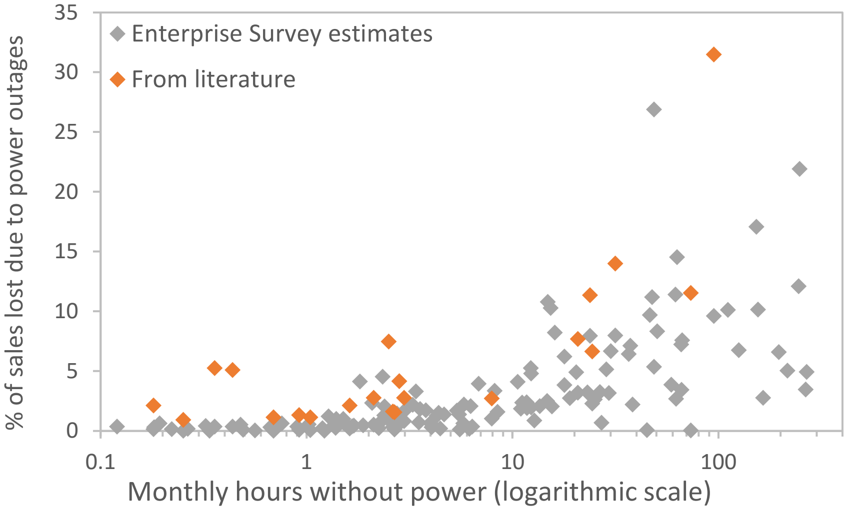
In the case of water and transport outages self-reported sales losses are not available in the Enterprise Surveys. Instead, Section 4.3 and 4.4 use a harmonized global dataset of firms to assess the nature and extent of the losses associated with infrastructure disruptions. In particular, it estimates the size of negative impacts due to infrastructure disruptions, and further investigates the transmission channels through which firms are affected; i.e. are firms primarily affected directly – i.e. production stops due to missing water, power or transportation service inputs – or through indirect effects – i.e. production stops due to supply chain interruptions?

3.1. Business costs of infrastructure disruptions: Self-reported losses due to power outages

This section uses self-reported Enterprise Surveys data to compute the value of sales lost due to electricity disruptions in our sample. It then constructs a regression model to estimate the impact of power outage durations on these sales losses. Aggregating firm data from 138 mostly small- and middle-income countries accounting for 32% of global GDP, it finds sales losses worth 81.6 billion 2018 real USD due to power outages. As a considerable fraction of firms (about 15%) did not respond to the question registering their sales, this number can be interpreted as a lower bound. The total annual blackout duration reported by firms is estimated to increase sales losses by 0.29 percentage points for each 100 hours of blackout.

On average, countries with higher power outage durations experience larger sales losses. A review of the literature described in Section 2 shows that the relationship between number of outages and sales losses is relatively flat for countries where firms, on average, face power outages of up to 10 hours (see Figure 3). For countries with longer outages, however, the sales losses appear to increase in an almost exponential pattern. Investigating this phenomenon at scale, our analysis confirms the non-linear and positive relationship between monthly hours without power and sales lost due to outages. Looking at the spatial distribution of relative losses, Figure 4 shows that Africa and South Asia are most affected.

Figure 3: Sample firms' average sales losses and power outages at the country-level



While all countries with high losses have long outage durations, countries exhibit varying capacities to deal with electricity disruptions. Figure 5 displays the 15 countries for which firms, on average, report the highest shares of sales lost due to outages. While all these countries suffer significant power outages, at this high level of outages the losses are no longer clearly related to electricity downtime. This indicates that the relationship is mediated by a number of other factors that determine firms' vulnerability to electricity network disruptions. Such factors include the sector a firm operates in, the competition it is exposed to, and the technology it employs for production. One key determinant of firms' vulnerability is possession of a power generator which will be discussed in the next section.

Figure 4: Sample firms' average sales losses aggregated to the country-level

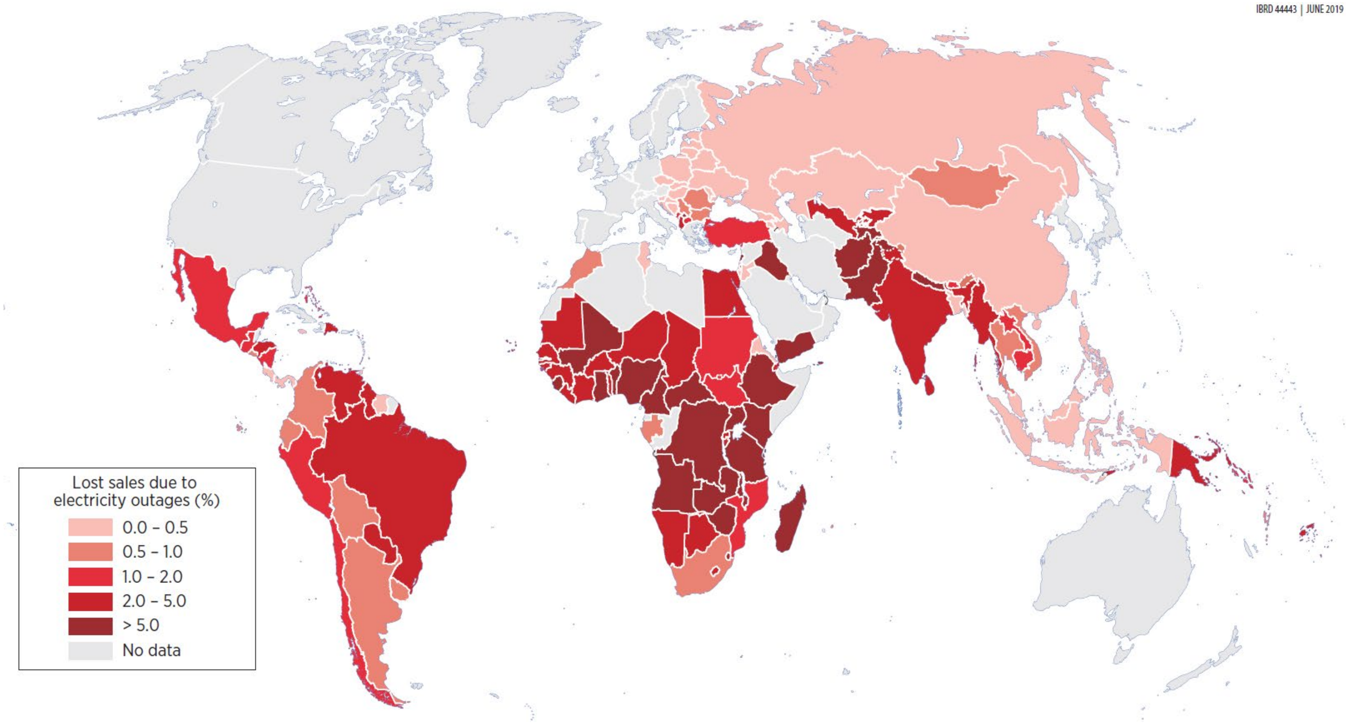
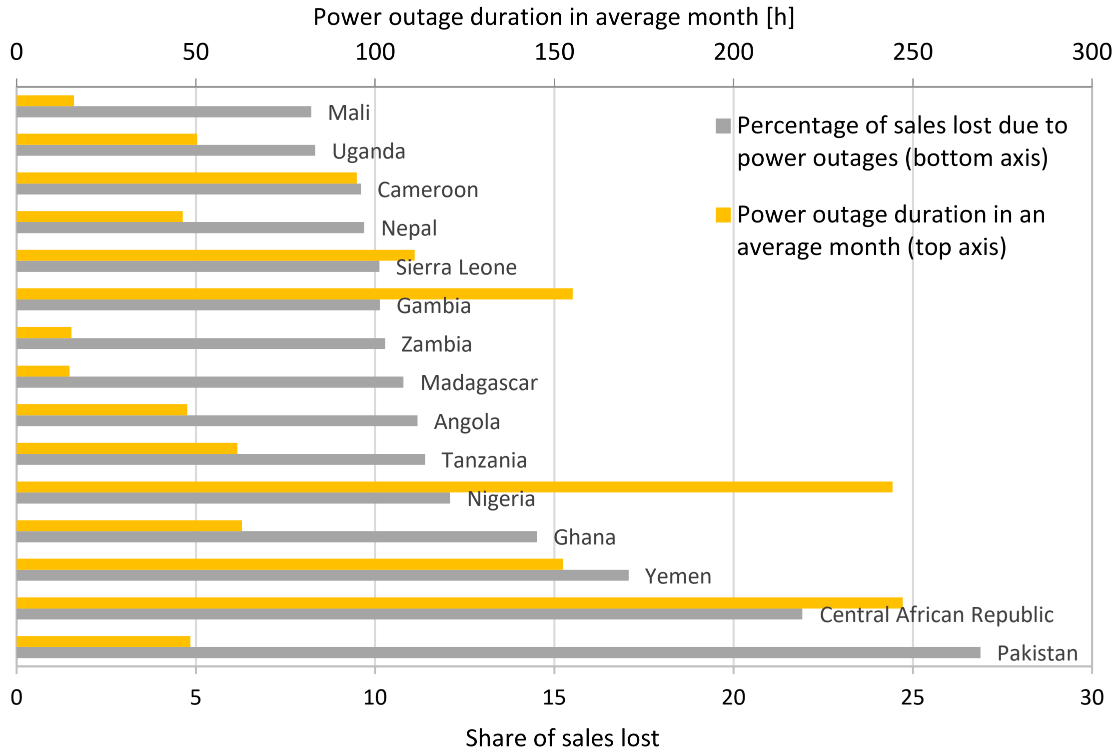
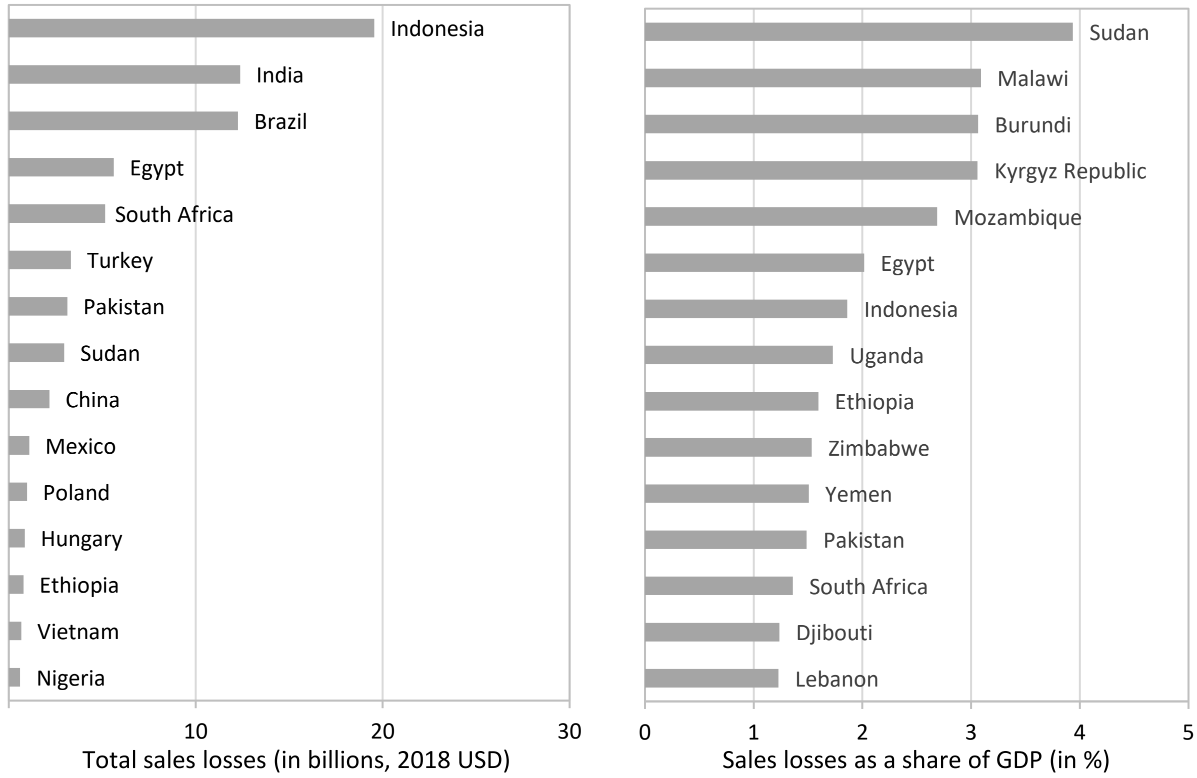


Figure 5: Sample firms' average sales losses and power outage durations for countries with highest percentages of sales lost



Large countries show the greatest absolute sales losses due to power outages, whereas smaller countries lose a larger fraction of GDP. This is illustrated by Figure 6 which disaggregates the global results into absolute numbers and absolute numbers as a share of GDP and shows the 15 most affected countries according to both measures. Sales lost as percentage of GDP in Figure 6 are significantly lower than share of sales lost as reported by the average firm in Figure 5. The set of countries affected most severely is quite different between the two measures. This is caused by several factors. First, the share of sales lost by the average firm is ignorant of firm size. If small firms experience more losses but larger firms can better cope with outages, the share of sales lost by the average firm will be higher than the total sales lost as percentage of GDP. Second, sales and GDP are quite different measures, as sales are ignorant of the value added a firm provides and thus its contribution to GDP. Third, the Enterprise Surveys primarily focus on the manufacturing and services sectors and thus covers a fraction of GDP that varies between countries. Finally, the fraction of firms answering the question about their sales and thus the degree to which a countries total economic activity is captured can differ among sample countries.

Figure 6: Total (left panel) and relative (right panel, as % of GDP) sales lost due to power outages for sample countries most affected



Evidence from selected countries shows that electricity disruptions have a significant negative effect on the performance of firms (Section 2). To assess this issue systematically and globally we analyze a model that estimates the impact of power outages (measured as total annual blackout duration) on firms' self-reported sales losses. More specifically, an electricity specific pooled ordinary least squares model is estimated with standard errors clustered at the regional level, and using sales losses relative to total sales as a dependent variable.

Harmonized core data is obtained from the World Bank's Enterprise Surveys, where firms report on the quality of electricity infrastructure, including the average monthly frequency and duration of service disruptions, as well as self-reported estimates of the annual loss of sales that are caused by electricity outages. It should be noted that the latter variable may in principle suffer from measurement errors. Without strict monitoring, firms may not be able to provide accurate estimates of outage-induced annual sales losses. Nevertheless, the data provides an indication of the perceived burden of power outages on businesses – consistent across this global panel of businesses.

We further control for a series of variables at the firm and country levels, including country and sector fixed effects. For this purpose, the data is obtained from either the Enterprise Surveys or the World Development Indicators database by the World Bank. Specifically, we control for firms' age, employment, inventory, state-ownership, export intensity, and generator ownership. Moreover, the model controls for the country-level output gap, electrification rate, water access rate, total population size, population density, urbanization and "Government Effectiveness", as measured by the Governance Indicators (Kaufmann, Kraay, & Mastruzzi, 2010).

The model is fit to a pooled dataset of 43,829 firms from 106 predominantly middle- and low- income countries, sampled between 2007 and 2014. Estimation is conducted by weighted ordinary least squares using normalized sample design stratification weights that sum to unity for each survey wave. Standard errors are clustered at the regional level to account for regressor correlation with region fixed effects and uncertainty about regressors' marginal effects being region-specific. The use of sectoral dummy interactions allows us to disaggregate slope coefficients by International Standard Industrial Classification (ISIC, revision 3.1) sectors, and thus assess sector-specific vulnerabilities.

Table 4: The impact of power outages on self-reported sales losses. Table 7 presents the full sectoral disaggregation of estimated coefficients.

Dep.: Relative blackout sales losses	(I)	(II)	(III)
Model variables	No interactions	with 2nd order term	with ISIC interactions
Blackout	0.0029***	0.0073***	0.0066***
annual hours	*(0.0004)*	*(0.0009)*	*(0.0009)*
Blackout^2		-0.0008***	-0.0008***
second order term, x10^{-3}		*(0.0001)*	*(0.0001)*
Blackout x ISIC:			*see Annex A.3*
Firm age	-0.0056	-0.0032	-0.0019
years since official registration	*(0.0056)*	*(0.0056)*	*(0.0055)*
Employment	-0.0025***	-0.0023***	-0.0020***
number of full time employees	*(0.0006)*	*(0.0006)*	*(0.0005)*
Inventory	0.0020	0.0017	0.0017
days for most important input	*(0.0028)*	*(0.0027)*	*(0.0026)*
State ownership	-0.0001	0.0034	0.0040
in %	*(0.0110)*	*(0.0122)*	*(0.0123)*
Export orientation	-0.0056*	-0.0047	-0.0050*
% of total sales	*(0.0030)*	*(0.0029)*	*(0.0028)*
Generator ownership	0.3628	0.2225	0.2125
Dummy	*(0.3929)*	*(0.3910)*	*(0.3888)*
ISIC Sector Fixed Effects	YES	YES	YES
Output Gap	0.1859**	0.1732*	0.1746*
HP residual as % of HP trend	*(0.0924)*	*(0.0913)*	*(0.0906)*

Electrification	-0.0124	-0.0254	-0.0289
% of population	*(0.0995)*	*(0.0893)*	*(0.0872)*
Water access	0.4148*	0.3617*	0.3816*
% of population	*(0.2201)*	*(0.2158)*	*(0.2067)*
Population	0.3123**	0.3006**	0.2649*
in mio	*(0.1469)*	*(0.1531)*	*(0.1474)*
Population density	-0.1246***	-0.1102***	-0.1024***
in 1/km^2	*(0.0409)*	*(0.0419)*	*(0.0392)*
Urbanisation	-0.0759	0.1100	0.1525
% of population	*(0.3891)*	*(0.3524)*	*(0.3591)*
WGI: Government Effectiveness	-4.5237*	-5.2523**	-4.9618**
Index, standard normal	*(2.5907)*	*(2.5074)*	*(2.4447)*
Country Fixed Effects	YES	YES	YES
N	43,829	43,829	43,829
R^2	0.31	0.34	0.34

Estimated with weighted OLS, normalised survey stratification weights applied. Standard errors in parenthesis, clustered within regions. Significance levels: *** 0.01, ** 0.05, * 0.10.

The estimates confirm that power outages have a significant adverse impact on firms. Most notably, the total annual blackout duration reported by firms is estimated to increase sales losses by 0.29 percentage points for each 100 hours of blackout (Table 4, model I). The estimated blackout effect is highly significant and robust, and can be seen to be concave: The squared total blackout time is significantly negative, thus suggesting a diminishing impact of each additional blackout hour. Specifically, the first 100 hours of blackout duration have a much more pronounced impact and reduce sales by 0.73 percentage points (Table 4, model II).

In addition to electricity outages, several control variables are estimated to have significant effects on blackout related sales losses. Most notably, larger firms, i.e. those with higher employee headcounts tend to report smaller sales losses. The country level output gap control variable (constructed based on the Hodrick-Prescott Filter) confirms that blackouts are costlier during booms as they curbing economic upswings. Moreover, higher governance standards are also estimated to reduce disruption impacts significantly.

By introducing an interaction term between blackout duration and the ISIC sectoral classification (Table 4 model III), the estimates also document significant sectoral heterogeneity. For the sake of brevity, the results for 31 economic sectors are reported separately in Annex A.3. These estimates suggest that manufacturing sectors such as oil refineries, producers of basic metals, precision instruments, and motor vehicle industries are particularly hard hit by power outages. By contrast, construction and logistics firms tend to be less vulnerable.

3.2. The cost of back-up generation of electricity due to power outages

Facing frequent electricity outages, a common response strategy by firms is to operate their own back-up generators, usually powered by diesel. While these generators enable firms to bridge power outages, they also require firms to purchase, install, maintain, and operate costly machinery. These expenses mean that generators tend to be less affordable for smaller firms with limited cash reserves. As a result, generator ownership is significantly higher among large firms, as shown in Figure 7 for 78,139 firms in 137 countries covered by the Enterprise Surveys.[2] Back-up generation is particularly common in low-income countries, as they are more prone to experiencing unreliable electricity supply through the central grid Figure 8.

Figure 7: Generator ownership and usage relative to firm size (based on World Bank Enterprise Surveys)

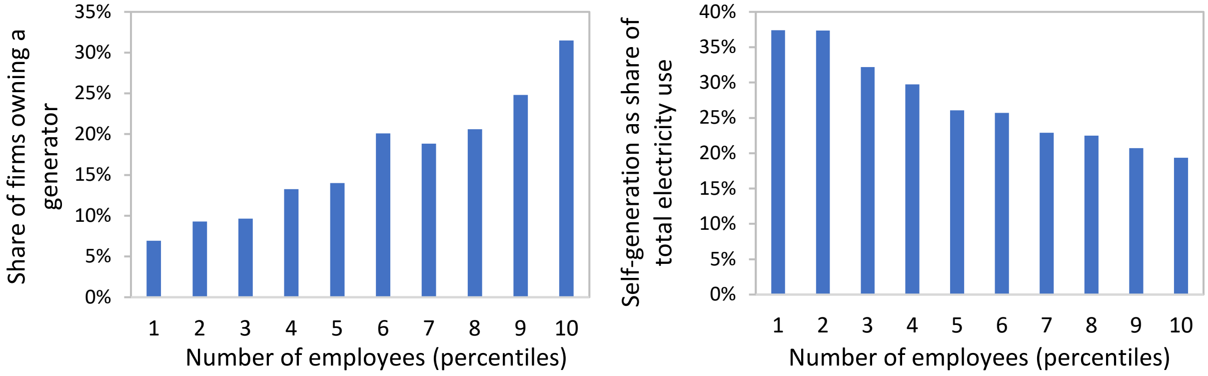
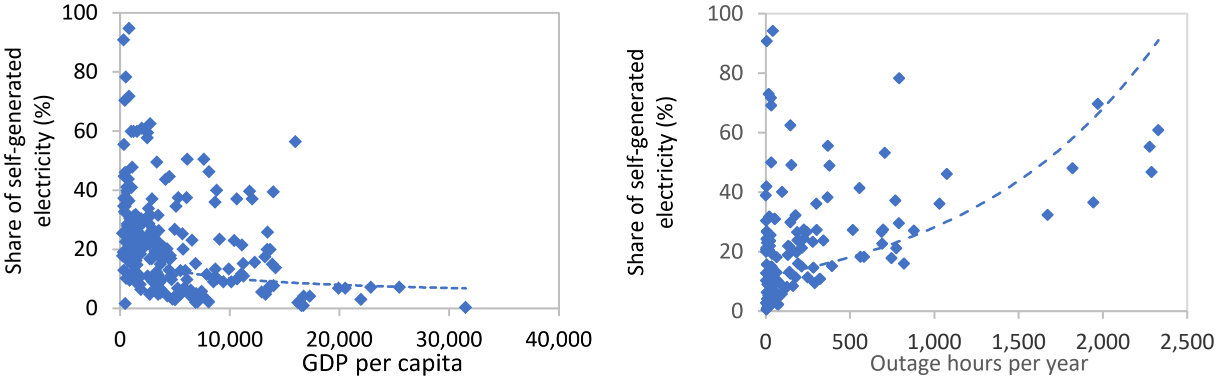


Figure 8: Self-generated electricity relative to wealth and power network reliability (based on World Bank Enterprise Surveys)



Various studies have shown that such self-generation is significantly more expensive than conventional grid supply (Adenikinju, 2003; Foster & Steinbuks, 2009). For instance, for 25 African countries, Foster & Steinbuks (2009) show that self-generation is on average three times as expensive as national electricity tariffs. Despite these extra costs, firms from the 137 countries covered by the World Bank's Enterprise Surveys generate on average 22.3% of their electricity needs using back-up generators. In the top 20 countries the self-generation share is as high as 40%. These figures suggest that self-generation impose significant costs on firms around the world and cannot be disregarded.

By estimating the installed self-generation capacity and the total annual self-generation amount, it is possible to estimate the costs of back-up electricity generation in the industrial sectors of 129 countries. For this purpose both the annualized up-front investment costs and the operation costs are taken into account.

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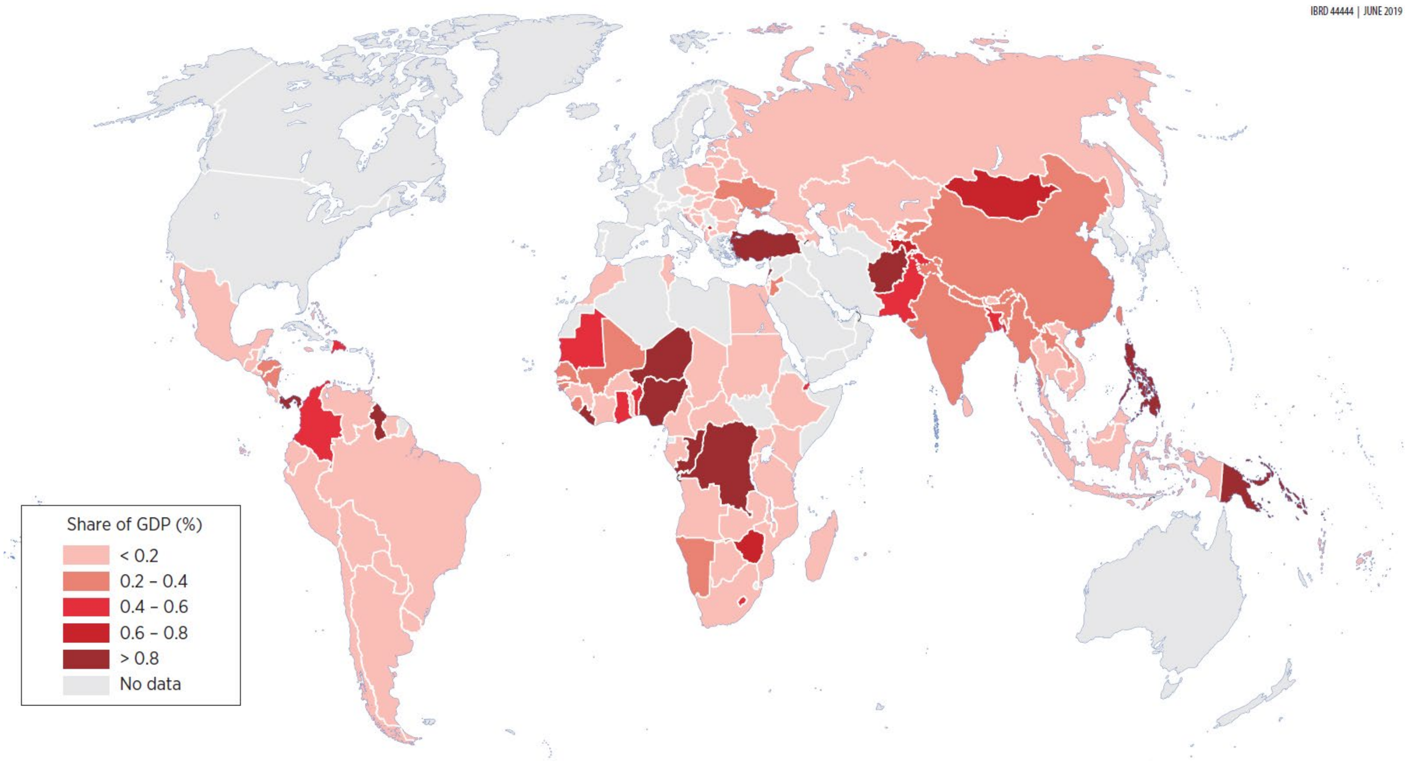
[2] Information on generation is not available in Sweden, which was excluded from the analysis.

Up-front investments in back-up generation: Following a review of the literature on self-generation, we apply an annualized cost approximation of US$0.032 per each kWh of self-generated electricity (ESMAP, 2007). Self-generated electricity in the industrial sector is estimated using estimates of electricity consumption of the industrial sector and self-reported share of back-up generation from the Enterprise Surveys. This yields total up-front investments in back-up generation in the order of US$ 6 bn per year.

Operating costs of back-up generation: Evidence from around the world suggests that operating a generator is more expensive than the electricity purchased from a central grid. Based on empirical studies on the cost of self-generation, we apply a price markup factor of 2 over the national electricity tariff (Foster & Steinbuks, 2009). Using the same estimate of self-generated electricity as in the assessment of up-front investments in back-up generation, we then estimate the annual operating costs to be in the order of US$ 59 bn each year.

Overall, unreliable power supply can be estimated to cause firms in the industrial sector to spend about US$ 65 billion per year on back-up self-generation – corresponding to 0.28% of GDP of the 129 sampled countries. In some countries, electricity self-generation costs can even be higher than 0.8% of GDP (Figure 9). Back-up costs are mainly driven by a few countries: the Chinese industrial sector bears half of the global self-generation cost due to the unreliability of its power network.

Figure 9: Sample firms' average self-generation costs aggregated to the country-level (as % of GDP)



3.3. Business costs of infrastructure disruptions: Utilization losses

Frequent disruptions of electricity, water or transport infrastructure often mean that firms are unable to utilize their full production capacity. Capacity utilization is a common measure of the effectiveness with which a firm converts its resources into output – and it is reported in the Enterprise Surveys. A firm that is frequently forced to halt production – for instance due to power outages, or due to input shortages caused by transport disruptions or upstream production stops – will be operating below its full capacity, i.e. have relatively lower levels of capacity utilization. This in turn will affect firm-level factor productivity and sales.

This section focusses on the capacity utilization of firms and distinguishes and assesses direct and indirect infrastructure disruptions impacts by extending the analysis to power, water and transport disruptions.

Unlike in the case of power outages, the Enterprise Surveys do not directly ask firms about the sales losses associated with water outages and transport disruptions. However, considering utilization reductions due to infrastructure disruptions in addition to self-reported sales losses makes it possible to estimate the firm-level cost of water and transport disruptions – in addition to power outages. Moreover, this estimation strategy presents two advantages. First, we are able to verify the sales loss estimates due to power outages obtained in the previous section. If the direct effect of electricity disruptions on utilization rates are estimated to be in the same order of magnitude as on sales losses, this would support the relevance and validity of the approach. It would also address the potential issue of measurements errors of self-reported sales losses due to power outages. Second, it is important to recognize that the indirect effects of infrastructure disruptions can potentially significantly exceed direct effects. For instance, even if a firm is not directly affected by infrastructure breakdowns (e.g. by experiencing a power outage on-site), it may still be forced to stop production as interruptions along the supply chain stifle input supply or output demand. Such indirect effects are unlikely to be taken into account by firms in their self-reported sale losses estimates due to electricity outages but will be included in the infrastructure utilization rates.

Unfortunately, the ES do not provide information about supply chain linkages. Instead, our econometric strategy proxies supply chain disturbances using regional disruption levels. Specifically, we average blackout and water supply interruption durations for all firms in any given region and introduce this region-level variable as a separate regressor into the regression model. We also interact it with the firm-specific disruption level to distill the pure direct and indirect impacts on utilization rates.

To assess this issue systematically we analyze a model that simultaneously estimates the impact of water, electricity, and transport disruptions on firms' utilization rates. The model is fit to a pooled dataset of 29,675 firms from 95 predominantly middle-income countries, sampled between 2007 and 2014. Estimation is conducted by weighted ordinary least squares using normalized sample design stratification weights that sum to unity for each survey wave. Standard errors clustered at the regional level to account for regressor correlation with region fixed effects and uncertainty associated with region-specific marginal effects.

As in Section 4.1, the model is based on a harmonized global panel dataset constructed from the World Bank's Enterprise Surveys. As part of these surveys, firms report on the quality of water and electricity infrastructure, including the average monthly frequency and duration of service disruptions. Firms also report transport disruptions using a subjective ordinal scale. These firm-specific subjective measures allow us to compute regional average disruption levels for blackouts, water shortages and transport disruptions. Those region-level variables can then be used to estimate how disruptions outside any firm's boundaries affect individual firms – that is, indirect effects. Results for this approach are presented in Table 5.

Table 5: Direct vs. Indirect (supply chain mediated) impacts

Dependent: Utilization Rate	(I)	(II)	(III)
Model variables	disruptions only	firm-level controls	firm + country controls
Blackout	-0.0013*	-0.0014	-0.0025***
annual hours	(0.0008)	(0.0010)	(0.0008)
Region. blackout level	0.0007	0.0000	-0.0015
annual hours, average	(0.0015)	(0.0014)	(0.0012)
Blackout x reg. blackout level	0.0005	0.0006	0.0010***
interaction, $x10^{-3}$	(0.0004)	(0.0004)	(0.0003)
Water supply disruption	-0.0016***	-0.0018***	-0.0013**
annual hours	(0.0005)	(0.0006)	(0.0005)
Region. water disruptions	-0.0057**	-0.0055**	-0.0010
annual hours, average	(0.0025)	(0.0027)	(0.0015)
Water dis. x region. water dis.	0.0011**	0.0011**	0.00035
interaction, $x10^{-3}$	(0.0004)	(0.0004)	(0.0003)
Transport problems	-2.08***	-2.15**	-1.73**
categorial, 0 (none) to 5 (very severe)	(0.79)	(0.86)	(0.82)
Region. transport problems	-2.27*	-1.40	0.85
categorial, 0 (none) to 5 (very severe)	(1.28)	(1.44)	(1.61)
Trans. prob. x reg. trans. prob.	1.20**	1.22*	0.93
interaction	(0.55)	(0.63)	(0.61)
Firm age		0.12***	0.090***
years since official registration		(0.020)	(0.018)
Employment		0.015***	0.012***
number of full time employees		(0.002)	(0.003)
Inventory		-0.013**	-0.003
days for most important input		(0.006)	(0.006)
State ownership		-0.006	-0.020
in %		(0.042)	(0.042)
Export orientation		0.011	0.016
% of total sales		(0.011)	(0.010)
Generator ownership		1.645**	2.486***
Dummy		(0.693)	(0.711)
ISIC Sector Fixed Effects		YES	YES
Output Gap			0.094
HP residual as % of HP trend			(0.219)
Electrification			-0.029
% of population			(0.174)
Water access			-0.426
% of population			(0.433)
Population			0.032
in mio			(0.243)
Population density			0.005
in 1/km^2			(0.051)
Urbanization			0.556
% of population			(0.465)
WGI: Government Effectiveness			7.132*
Index, standard normal			(4.217)
Country Fixed Effects			YES
N	38369	30208	29675
R^2	0.02	0.04	0.14

Estimated with weighted OLS, normalised survey stratification weights applied. Standard errors in parenthesis, clustered on region. Significance levels: *** 0.01, ** 0.05, * 0.10.

First, these estimates suggest a robust and significant negative impact of infrastructure disruptions on firm utilization rate. Power outages, water outages, and transportation issues all contribute to reducing utilization, and therefore productivity and revenues.

Second, estimates indicate that for water and transport, indirect effects may be as or even more important than direct impacts, while the indirect impact of power outages seems to be smaller. However, indirect effects are imperfectly measured using regional disruption levels, as point estimates for region-level variables are sensitive to different controls and show large standard errors.[3] Nonetheless, one implication is that estimates looking only at direct impacts of infrastructure disruptions may be missing a large part of the economic cost.

Third, the interaction term (between direct and indirect impacts) is positive for all types of infrastructure. This means that direct impacts are less severe if the firm's backward and forward linkages are disturbed anyways – and conversely: supply chain mediated indirect effects cause less harm when the firm already suffers from direct disruptions.

The estimated model suggests that infrastructure disruptions have a significant economic cost in the form of reduced business utilization rates. In the case of electricity outages, measured by the annual self-reported total blackout duration, this effect is robust significant across model specifications. Following this estimate, 100 additional hours of blackout decrease utilization by 0.13 to 0.32 percentage points on average (Table 4 model III).4 Note that this estimate is close to the results in section 4.1. based on self-reported losses, which suggest that 100 hours of blackout would decrease the annual utilization rate by about 0.29 percentage points in the model without interaction (Table 4 model I). This makes us confident that our identification strategy in the previous section is valid and thus also provides reliable estimates for water and transportation.

A similar result is obtained for water outages, measured by the annual total outage duration. In this case, 100 additional hours of water outages are estimated to decrease utilization by up to 0.19 percentage points on average.[5] From among the three infrastructure variables considered here, water has the weakest explanatory power according to standardized beta coefficients (not shown).

For transport, there is also a significant impact of transport problems on the utilization rate, but numerical results are difficult to interpret since the metric is qualitative. In fact, it does not allow to investigate marginal effects, and we can only compare the *proportion* of direct to indirect effects.

For assessing the impact of marginal increases in transport reliability, we use an alternative measure of transport reliability, the Logistic Performance Index' (LPI) "timeliness" sub-indicator (Jaramillo et al., 2018). LPI can be used to proxy reliability, resilience and steadiness of transport infrastructure, i.e. the absence

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[3] Note that for transport, various country-level characteristics correlate with transport quality, making it hard to pin down indirect effects.

[4] The average firm in the sample experiences 253.5 hours of blackout annually, while 10% of all firms face 720 hours or more.

[5] The majority of firms does not face any water supply disruptions while a few firms have to cope with long and frequent interruptions. The top 5% of most disrupted firms face at least 120 hours, the top 1% faces 2700 hours or more.

of disruptions.[6] Being a country-level variable, it well reflects the systemic nature of an economy's transport system and is not an ordinal perception index. This means it allows level comparison across firms and meaningful interpretation of marginal effects in the model. However, as a country-level variable, the LPI does not allow us to distinguish firm-level and regional variation (which is necessary for distinguishing direct and indirect effects). The results for this section are presented in Annex A.4.

Transport reliability is shown to have a positive and highly significant impact on firms' utilization rates. Increasing the Logistics Performance Index on *Timeliness* by 1 point – which, for instance, corresponds to the difference between Tanzania and South Korea – raises firms' utilization rates by 5.8 percentage points on average (Annex A.4, model II). Introducing other country-level controls barely moves the point estimate, however, it inflates the standard error due to collinearity with the country-level LPI variable which also changes slowly across years. Among infrastructure disruption variables, transport is most potent to explain dependent's variation.

Finally, governance quality as measured by the World Governance Indicators strongly improves firms' utilization rates. While Table 5 shows results for the sub-indicator "Governance Effectiveness", any other World Governance Indicator – such as "Control of Corruption" – yields very similar estimation results (not shown). Specifically, a one-step increase – for example the difference between Japanese and South African government effectiveness – would raise average utilization by roughly 7 percentage points (Table 5, model III). Not only is the marginal effect large, but also the variance explained, as measured by standardized beta coefficients (not shown). For further details refer to Kornejew, Rentschler, and Hallegatte (2019).

Note that using a fractional response regression model with a logit or probit link function – which in principle better suits the bounded dependent variable – has virtually no impact on these conclusions. We therefore present standard OLS coefficients for easier interpretation.

3.4. The cost of unreliable infrastructure to firms in developing countries

This section estimates the global losses caused by infrastructure disruptions that reduce firms' utilization rates. For 118 mostly low- and middle-income countries, unreliable infrastructure leads to utilization losses worth 151 billion real 2018 USD, amounting to 0.59% of sample GDP.

This section uses a slightly modified version of the model in the previous section to compute these costs. First, firm-level utilization rate reductions due to unreliable power, water, and transport infrastructure are estimated in a regression controlling for the same variables as described above. In contrast to the model in Table 5, only direct effects of the infrastructure variables are included, dropping regional terms as well as interactions. While the regional variables are useful to disentangle direct and indirect effects, this distinction is not necessary for the estimation of the overall cost of disruptions. We apply weights that are modified to include employment as a proxy of firm's contribution to national value-added. Using these weights, we aggregate within each country to obtain a national estimate of the utilization losses due to unreliable infrastructure. Country-level costs are computed by applying the weighted utilization losses to nation GDP. Where several survey rounds are available for one country, only the newest one is considered.

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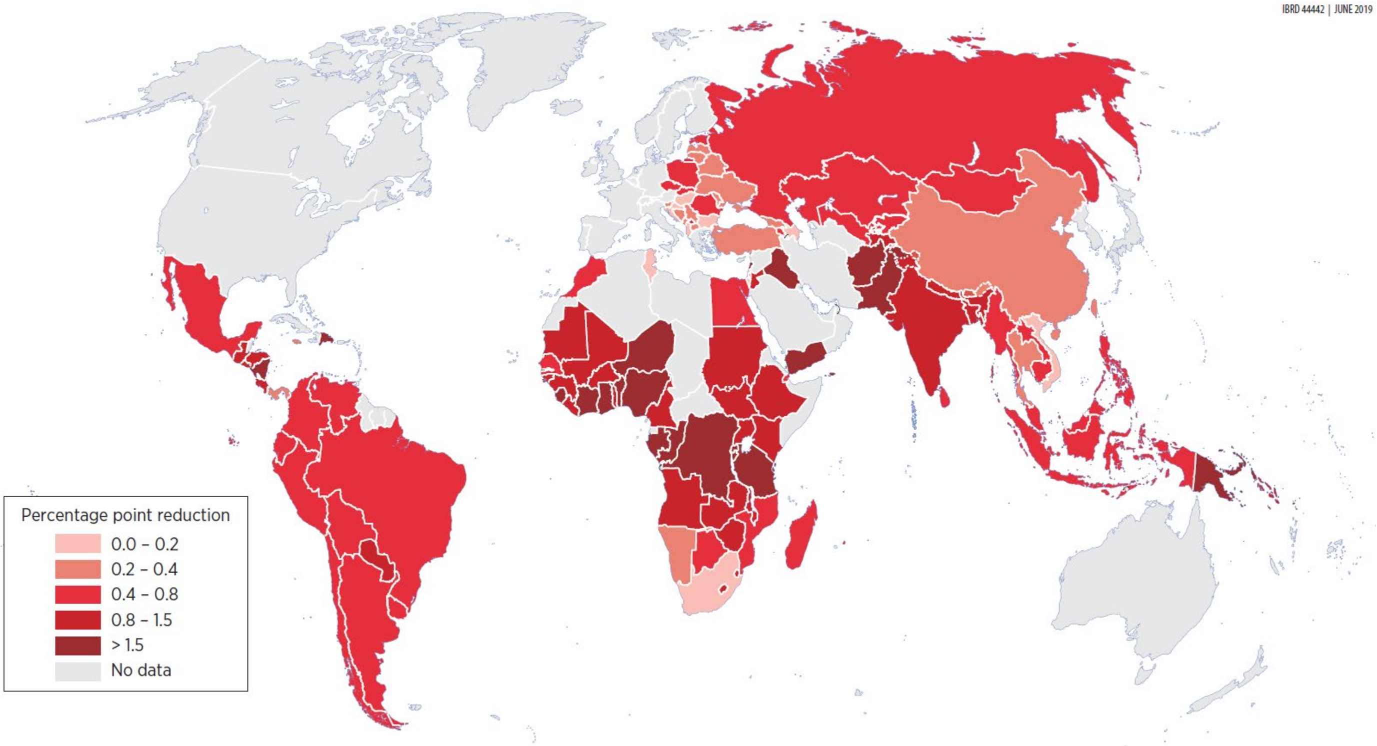
[6] The LPI is a benchmarking tool designed to help countries identify the challenges and opportunities in trade logistics. It benchmarks countries in six categories related to trade logistics, including the efficiency of customs, infrastructure and timeliness, and computes a score between 1 (low logistics performance) to 5 (high).

Over two-thirds of global utilization losses are caused by unreliable transportation infrastructure, about a quarter by electricity disruptions, and only a small fraction is attributable to water. This result is obtained by separating utilization rate losses into the three types of infrastructure considered in this analysis. Transport infrastructure accounts for losses of US$107 billion, or 0.42% of sample GDP. Disruptions to electricity supply account for US$38 billion and water disruptions cause utilization rate losses of US$6 billion.

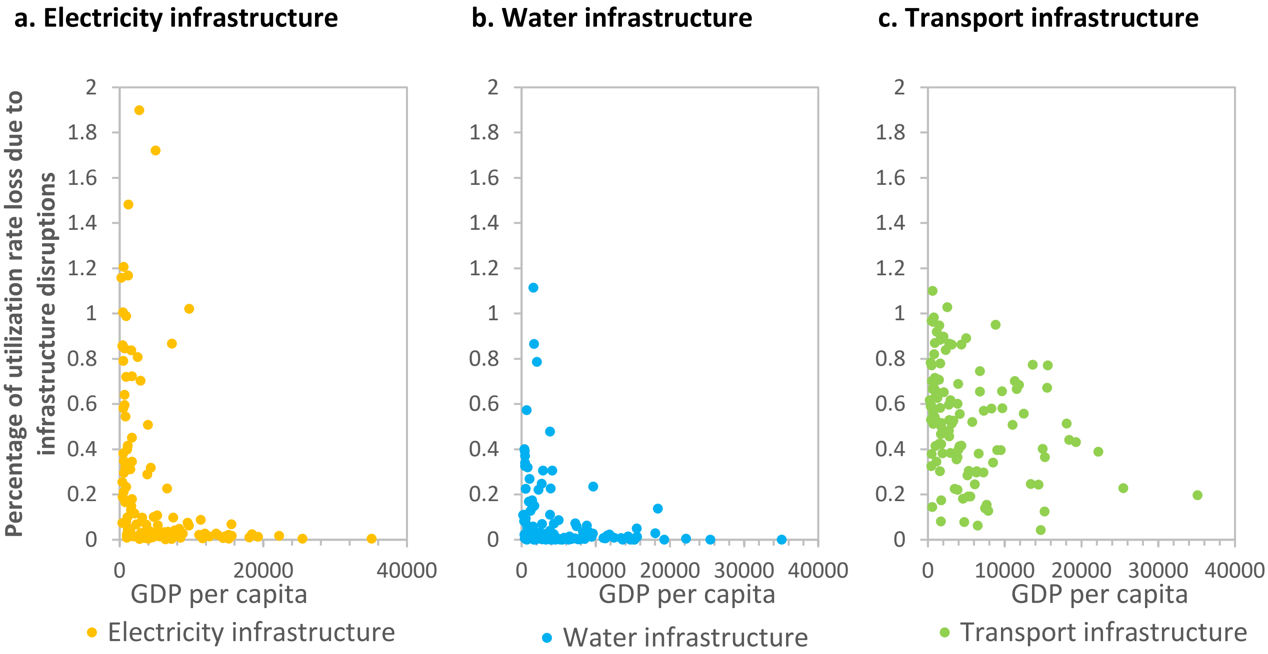
Figure 10: Country-wide average utilization rate losses due to electricity, water, and transport infrastructure disruptions



All countries are affected by utilization losses due to unreliable transport infrastructure. Figure 11 shows the utilization rate losses for each country due to transport, electricity, and water infrastructure disruptions, respectively. Unused capacity caused by transport problems is distributed quite uniformly across countries, with few countries experiencing either very high or very low costs. This persistence of transportation losses explains the large contribution to the overall loss figure; the damage that unreliable transportation infrastructure deals to the economy affects all countries and appears to be hard to eliminate.

Looking at electricity outages, firms in some countries are inhibited severely whereas other countries are barely affected.

Figure 11: Utilization rate losses from infrastructure disruptions, by type of infrastructure at country level



Note: Data points represent 118 countries.

Figure 12 and Figure 13 show the most affected countries overall and by infrastructure type, respectively. In some countries, unreliable electricity infrastructure causes large fractions of industry capacity to remain unused, often significantly more so than transportation problems. At the same time, firms in many countries are barely affected by power outages as 46% of countries experience utilization losses of less than 0.05% due to electricity. Other than in the case of transportation disruptions, many countries appear to be successful in eliminating their firms' losses due to unreliable electricity.

Unreliable water infrastructure has a small affect in most countries. Whereas some countries' firms suffer significant losses from disrupted water infrastructure, most countries appear to be affected only moderately. This might indicate countries' success in eliminating outages as well as firms' lower reliance on water infrastructure.

Figure 12: Countries with greatest overall utilization rate losses due to all infrastructure disruptions

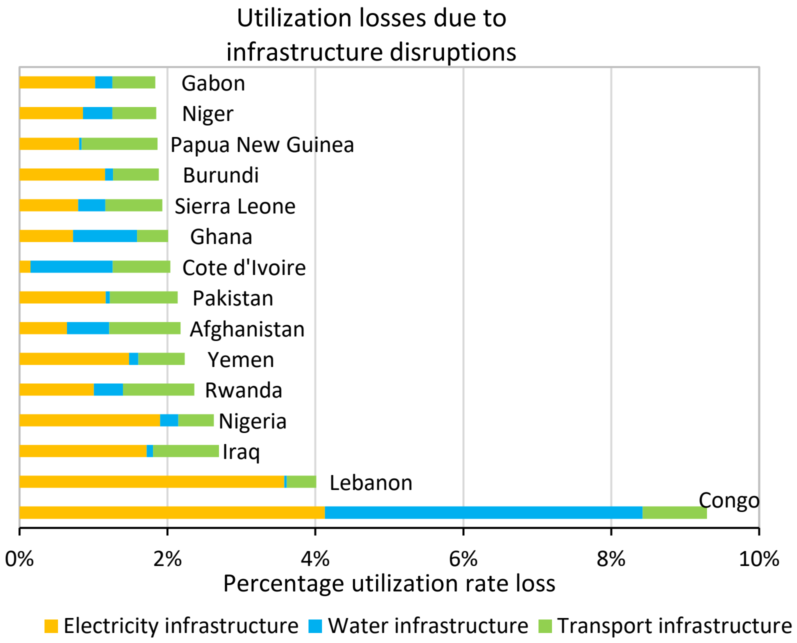
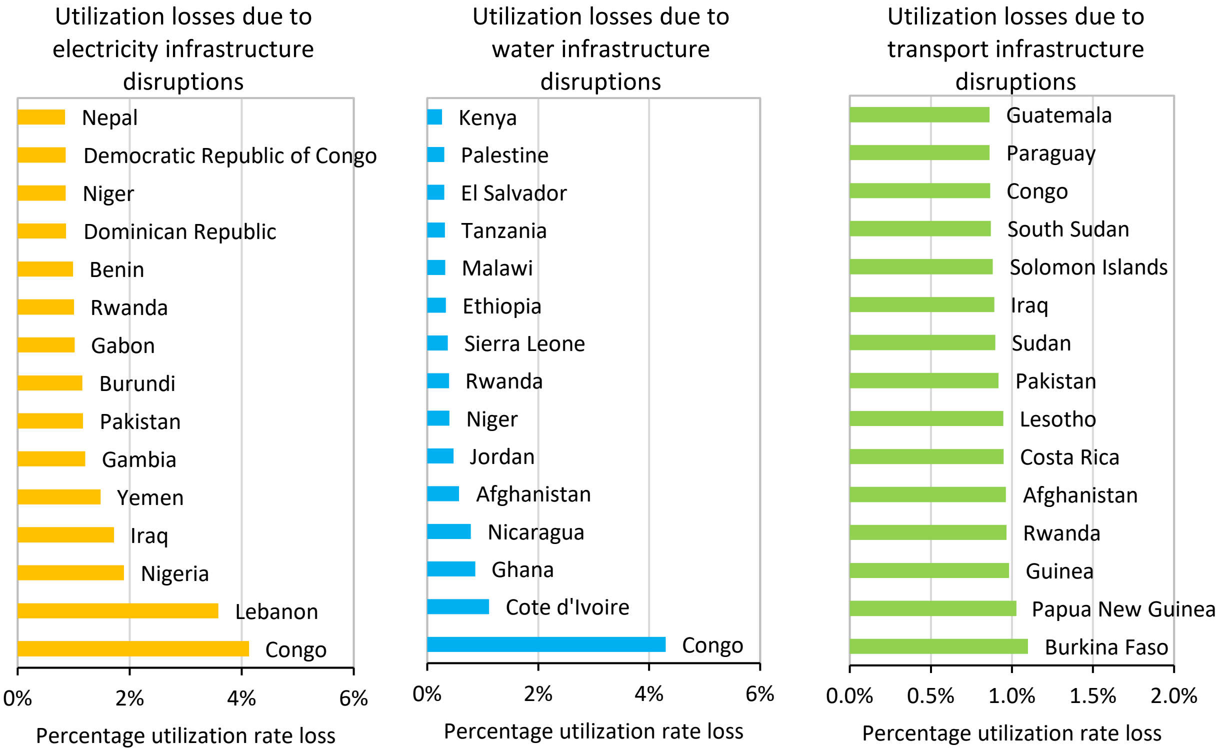


Figure 13: Countries with greatest utilization rate losses by type of infrastructure disruption; left panel: electricity infrastructure, middle panel: water infrastructure, right panel: transport infrastructure



4. Conclusions

Without a thorough understanding of the economy-wide costs of infrastructure disruptions, policy makers are ill-equipped for identifying, prioritizing and implementing adequate investments and reforms for enhancing the reliability, quality, and resilience of their infrastructure systems.

Disruption of infrastructure services affect firms in every economy around the world. However, disruption frequencies vary widely across as well as within economies. Whether or not a firm will have to cope with blackouts, water shortages, logistical obstacles or loss of telecommunication ultimately depends on the interaction of country-level as well as firm-level exposure and resilience factors. The quality of infrastructure is generally linked closely to the level of economic development, proxied by GDP per capita in this paper and by the quality of the institution in Kornejew, Rentschler, & Hallegatte (2019). For transport, water, electricity, and infrastructure more generally, more developed countries tend to have fewer disruptions and higher perceived infrastructure reliability. However, the data shows that there exist significant differences in infrastructure quality between countries with the same level of development, what is explained in part by firm-level factors. On average, larger firms tend to experience less water disruptions and blackouts while at the same time many outages cause firms to invest in own back-up generation. Exposure to disruptions is also highly dependent on the sector in which the firm operate, further suggesting that effective measures are taken to shield critical infrastructure to prevent outage-inflicted damage from spreading further. Finally, concerning natural hazards, extreme precipitation and storms are positively associated with water disruptions, while transport networks are affected by storms.

Reliable and efficient infrastructure systems are crucial to enable firms to follow long-term planning, and to maximize their capacity, without the need to invest excessively in expensive back-up or contingency technology. A thorough analysis of electricity network systems shows that, in the 138 countries covered by the Enterprise Surveys, sales losses are worth US$81.6 billion due to power outages (lower bound estimate). The total annual blackout duration reported by firms is estimated to increase sales losses by 0.29 percentage points for each 100 hours of blackout. When facing frequent electricity outages, a common response strategy is to operate their own back-up generators. While these generators enable firms to bridge power outages, they also require firms to purchase, install, maintain, and operate costly machinery. Unreliable power supply can be estimated to cause firms in the industrial sector to spend about US$ 65 billion per year on back-up self-generation – corresponding to 0.28% of GDP of the 129 sampled countries.

Overall, and building on a harmonized firm-level dataset collected by the World Bank's Enterprise Survey in 138 mostly small- and middle-income countries accounting for 32% of global GDP, models suggest a robust and significant negative impact of infrastructure disruptions on firm utilization rates of water, electricity and transport infrastructure. For 118 countries, unreliable infrastructure (water, transport and electricity) leads to utilization losses worth US$151 billion real 2018 USD, amounting to 0.59% of sample GDP. Therefore, for as long as infrastructure systems remain disruption-prone, this will have substantial adverse effects on the continuity of production and service delivery, affecting the smooth functioning of supply chains, diminishing aggregate productivity, and restricting the ability of firms to trade and compete internationally.

More importantly, estimations show that for water and transport, indirect effects may be as or even more important than direct impacts. One implication is that estimates looking only at direct impacts of infrastructure disruptions may be missing a large part of the economic cost.

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Appendix

Annex A.1

Table 6: Country-level determinants of disruptions

Dependent:	Blackouts	Water disruption	Transport problems	Transport problems	Transport problems	Transport problems
Model variables	Baseline	Baseline	No governance, no spending	No governance	Baseline	With county FE
Output Gap	-21.4333	-21.1625	0.0138***	0.0075	-0.0006	-0.0093*
HP residual as % of HP trend	*(21.6779)*	*(19.5278)*	*(0.0053)*	*(0.0082)*	*(0.0066)*	*(0.0055)*
GDP Growth	7.4593	8.5404	-0.0128***	-0.0160***	-0.0065*	0.0014
annual, in %	*(7.2893)*	*(6.0843)*	*(0.0033)*	*(0.0041)*	*(0.0035)*	*(0.0021)*
Electrification	-2.8383	-2.6508	0.0003	-0.0054*	-0.0020	0.0012
% of population	*(3.6982)*	*(2.1407)*	*(0.0017)*	*(0.0030)*	*(0.0025)*	*(0.0045)*
Water access	-8.4012	1.3151	0.0070**	0.0077	0.0016	-0.0286*
% of population	*(7.0578)*	*(1.8621)*	*(0.0034)*	*(0.0054)*	*(0.0049)*	*(0.0169)*
Population	0.8897**	-0.0201	0.0001***	0.0002	0.0001	-0.0038
in mio	*(0.3648)*	*(0.0729)*	*(0.0000)*	*(0.0002)*	*(0.0002)*	*(0.0033)*
Population density	-0.1565	-0.1126	0.0006***	0.0005***	0.0004***	0.0015
in 1/km^2	*(0.1601)*	*(0.0873)*	*(0.0001)*	*(0.0001)*	*(0.0001)*	*(0.0014)*
Urbanisation	4.8294	2.7502	0.0088***	0.0104***	0.0045*	0.0369
% of population	*(4.9504)*	*(3.5266)*	*(0.0019)*	*(0.0025)*	*(0.0027)*	*(0.0354)*
WGI: Government Effectiveness	-184.0429**	-27.6857			0.3525***	0.2625*
Index, standard normal	*(79.3588)*	*(42.7362)*			*(0.0435)*	*(0.1342)*
Public road spending				0.1574***	0.0384	0.0315
per capita, in constant 2009 USD, log				*(0.0291)*	*(0.0262)*	*(0.0339)*
Country FE						YES
N (country-years)	207	207	1233	556	556	556
R^2	0.18	0.05	0.45	0.60	0.71	0.91

Estimated with OLS. Standard errors in parenthesis, clustered on countries. Public road spending includes both investment and maintenance expenditures. Significance levels: *** 0.01, ** 0.05, * 0.10.

Annex A.2

To assess the storm, drought and extreme rainfall exposure of all countries included in the ES, this paper uses global high-frequency climate data from the 5th global reanalysis (ERA5) conducted by the European Center for Medium-Range Weather Forecasts (ECMWF) using its Integrated Forecasting System (IFS).[7] As the dataset goes back as far as 1950, wind speed and precipitation data could be extracted for all years from 2000 onward, and for all 137 centroid coordinates of the respective countries included in the dataset.

More specifically, wind data is obtained at a six-hour frequency for all locations. To obtain a measure of storm frequency for a given country, we count all observations that exceed the 99.5th percentile from all wind speed observations in the studied country, across all years since 2000. It should be noted that reanalysis datasets like ERA5 tend to underrepresent high-intensity tail events, such as tropical cyclones and severe local convective storms (Hodges et al., 2017).

Similarly, precipitation data is modeled every 3 hours for each location. Once aggregated to obtain daily point estimates of precipitation levels, these measures are used to define extreme rainfall episodes and droughts events. In line with the approach taken for wind speeds, a drought hazard is defined as the annual precipitation deficit relative to the 6.7th percentile of the country-level precipitation observations, measured in percent. Abnormal precipitation peaks correspond to the number of days during which the cumulative precipitation levels are over the 95th percentile of the national precipitation observations.

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[7] Retrieved from https://www.ecmwf.int/en/forecasts/datasets/archive-datasets/reanalysis-datasets/era5.

Annex A.3

Table 7: Sector heterogeneity of the impact of power outages on the self-reported sales losses of firms

Dep.: Relative blackout sales losses	(I)	(II)	(III)
Model variables	No interactions	with 2nd order term	with interactions
Blackout	0.0029***	0.0073***	0.0066***
annual hours	*(0.0004)*	*(0.0009)*	*(0.0009)*
Blackout^2		-0.0008***	-0.0008***
second order term, x10^{-3}		*(0.0001)*	*(0.0001)*
Blackout x ISIC:			
M: Food and Beverages (Base)			.
interaction			.
M: Tobacco			0.0019
interaction			*(0.0014)*
M: Textiles			0.0009
interaction			*(0.0006)*
M: Clothing			0.0017*
interaction			*(0.0010)*
M: Leather products			0.0013
interaction			*(0.0009)*
M: Wood products			0.0012
interaction			*(0.0008)*
M: Paper products			0.0021
interaction			*(0.0014)*
M: Printed products			0.0001
interaction			*(0.0008)*
M: Coke, petrol refinery			0.0125***
interaction			*(0.0036)*
M: Chemicals			0.0011
interaction			*(0.0008)*
M: Rubber and plastics			0.0010
interaction			*(0.0011)*
M: Other non-metallic minerals			-0.0002
interaction			*(0.0010)*
M: Basic metals			0.0019**
interaction			*(0.0009)*
M: Fabricated metals			0.0007
interaction			*(0.0007)*
M: Machinery			0.0011
interaction			*(0.0008)*
M: Office, computing machinery			0.0063
interaction			*(0.0067)*
M: Electrical machinery			0.0013
interaction			*(0.0011)*
M: Radio, TV, Communication devices			0.0023
interaction			*(0.0041)*
M: Precision instruments			0.0021**
interaction			*(0.0009)*
M: Motor vehicles			0.0061***
interaction			*(0.0016)*
M: Other transport equipment			0.0007
interaction			*(0.0009)*
M: Furniture			0.0008
interaction			*(0.0007)*
Recycling			0.0021
interaction			*(0.0030)*
Construction			-0.0021

interaction			*(0.0014)*
Vehicle trade and repair			0.0181***
interaction			*(0.0020)*
Wholesale trade			-0.0013
interaction			*(0.0011)*
Retail trade			0.0013*
interaction			*(0.0008)*
Hotel and Restaurants			0.0031
interaction			*(0.0022)*
Land transport			-0.0017
interaction			*(0.0011)*
Auxiliary transport activities			0.0529***
interaction			*(0.0067)*
Programming			0.0001
interaction			*(0.0072)*
Firm age	-0.0056	-0.0032	-0.0019
years since official registration	*(0.0056)*	*(0.0056)*	*(0.0055)*
Employment	-0.0025***	-0.0023***	-0.0020***
number of full time employees	*(0.0006)*	*(0.0006)*	*(0.0005)*
Inventory	0.0020	0.0017	0.0017
days for most important input	*(0.0028)*	*(0.0027)*	*(0.0026)*
State ownership	-0.0001	0.0034	0.0040
in %	*(0.0110)*	*(0.0122)*	*(0.0123)*
Export orientation	-0.0056*	-0.0047	-0.0050*
% of total sales	*(0.0030)*	*(0.0029)*	*(0.0028)*
Generator ownership	0.3628	0.2225	0.2125
Dummy	*(0.3929)*	*(0.3910)*	*(0.3888)*
ISIC Sector Fixed Effects	YES	YES	YES
Output Gap	0.1859**	0.1732*	0.1746*
HP residual as % of HP trend	*(0.0924)*	*(0.0913)*	*(0.0906)*
Electrification	-0.0124	-0.0254	-0.0289
% of population	*(0.0995)*	*(0.0893)*	*(0.0872)*
Water access	0.4148*	0.3617*	0.3816*
% of population	*(0.2201)*	*(0.2158)*	*(0.2067)*
Population	0.3123**	0.3006**	0.2649*
in mil	*(0.1469)*	*(0.1531)*	*(0.1474)*
Population density	-0.1246***	-0.1102***	-0.1024***
in 1/km^2	*(0.0409)*	*(0.0419)*	*(0.0392)*
Urbanisation	-0.0759	0.1100	0.1525
% of population	*(0.3891)*	*(0.3524)*	*(0.3591)*
WGI: Government Effectiveness	-4.5237*	-5.2523**	-4.9618**
Index, standard normal	*(2.5907)*	*(2.5074)*	*(2.4447)*
Country Fixed Effects	YES	YES	YES
N	43829	43829	43829
R^2	0.31	0.34	0.34

Estimated with weighted OLS, normalised survey stratification weights applied. Standard errors in parenthesis, clustered within regions. Significance levels: *** 0.01, ** 0.05, * 0.10.

Annex A.4

Table 8: Infrastructure disruption impacts on firm utilization

Dependent: Utilization Rate	(I)	(II)	(III)
Model variables	disruptions only	with firm controls	with firm & country controls
Blackout	-0.0006	-0.0028***	-0.0014*
annual hours	(0.0008)	(0.0011)	(0.0007)
Water supply disruption	-0.0012*	-0.0022**	-0.0003
annual hours	(0.0006)	(0.0011)	(0.0006)
LPI: Timeliness	5.20***	5.85***	4.24
index, 1 (unreliable) to 5 (reliable)	(1.35)	(1.99)	(4.59)
Employment		0.007**	0.010***
number of full time employees		(0.003)	(0.003)
Firm age		0.115***	0.084***
years since official registration		(0.041)	(0.023)
Inventory		-0.019	-0.005
days for most important input		(0.012)	(0.007)
State ownership		-0.047	-0.089*
in %		(0.030)	(0.047)
Export orientation		-0.016	0.021**
% of total sales		(0.016)	(0.009)
Generator ownership		0.588	2.450**
Dummy		(1.153)	(0.972)
ISIC Sector Fixed Effects		YES	YES
Output Gap			0.277
HP residual as % of HP trend			(0.247)
Electrification			0.267
% of population			(0.273)
Water access			-1.790*
% of population			(1.000)
Population			-0.811
in million			(0.528)
Population density			0.265
in 1/km^2			(0.220)
Urbanisation			2.081**
% of population			(0.893)
WGI: Government Effectiveness			23.173***
Index, standard normal			(7.879)
Country Fixed Effects			YES
N	38,369	30,208	29,675
R^2	0.01	0.05	0.13

Estimated with weighted OLS, normalised survey stratification weights applied. Standard errors in parenthesis, clustered on region. Significance levels: *** 0.01, ** 0.05, * 0.10.

This table complements the results presented in Table 5, Section 4.3: here, transport disruptions are measured with the LPI index “Timeliness”, a country-level indicator that proxies the transport network quality and reliability. To accommodate this proxy, the firm-level dataset assembled from the Enterprise

Surveys was aggregated at the country level, preventing a differentiated analysis of the direct and indirect effects of infrastructure disruptions on utilization rates.

The estimated model suggests that infrastructure disruptions have a significant economic cost in the form of reduced business utilization rates. In the case of electricity outages, measured by the annual self-reported total blackout duration, this effect is robustly significant across model specifications. Following this estimate, 100 additional hours of blackout decrease utilization by about 0.28 percentage points on average (Table 8 model II).[8] Note, that this estimate is close to the results in section 4.3., which estimated that 100 hours of blackout would decrease the annual utilization rate by about 0.25 percentage points. This makes us confident, that our identification strategy in the previous section is valid and thus also provides reliable estimates for water and transportation.

A similar result is obtained for water outages, measured by the annual total outage duration. In this case, 100 additional hours of water outages are estimated to decrease utilization by up to 0.22 percentage points on average (Table 8, model II).[9] From among the three infrastructure variables considered here, water has the weakest explanatory power according to standardized beta coefficients (not shown).

Similarly, transport resilience is shown to have a positive and highly significant impact on firms' utilization rates. Introducing other country-level controls barely moves the point estimate, however, it inflates the standard error due to collinearity with the country-level LPI variable which also changes slowly across years. Increasing the Logistics Performance Index on *Timeliness* by 1 point – which, for instance, corresponds to the difference between Tanzania and South Korea – raises firms' utilization rates by 5.8 percentage points on average. Among infrastructure disruption variables, transport is most potent to explain dependent's variation.

Note that using a fractional response regression model with a logit or probit link function – which in principle better suits the bounded dependent variable – has virtually no impact on these conclusions. We nevertheless present standard OLS coefficients for easier interpretation.

Finally, governance quality as measured by the World Governance Indicators strongly improves firms' utilization rates. While Table 8 shows results for the sub-indicator "Governance Effectiveness", any other World Governance Indicator yields very similar estimation results.[10] Specifically, a one-step increase – for example the difference between Japanese and South African government effectiveness – would raise average utilization by roughly 23 percentage points. Not only is the marginal effect large, but also the variance explained, as measured by standardized beta coefficients (not shown). Similarly, the degree of urbanization exhibits considerable explanatory power for cross-country and temporal within-country differences in firm utilization.

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[8] The average firm in the sample experiences 253.5 hours of blackout annually, while 10% of all firms face 720 hours or more.

[9] The majority of firms does not face any water supply disruptions while a few firms have to cope with long and frequent interruptions. The top 5% of most disrupted firms face at least 120 hours, the top 1% faces 2700 hours or more.

[10] Similar results are obtained when using "Control of Corruption" as a measure of the governance quality (not shown).