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LIFELINES: THE RESILIENT INFRASTRUCTURE OPPORTUNITY

Background Paper

Candle in The Wind?

Energy System Resilience to Natural Shocks

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Abstract

This study finds that natural shocks—storms in particular—are a significant and often leading cause for power supply disruptions. This finding is based on 20 years of high frequency (i.e. daily) data on power outages and climate variables in 28 countries—Bangladesh, the United States and 26 European countries. More specifically: (1) Natural shocks are the most important cause of power outages in developed economies. On average, they account for more than 50 percent of annual outage duration in both the US and Europe. In contrast, natural shocks are responsible for a small share of outages in Bangladesh, where disruptions occur on a daily basis for a variety of reasons. (2) Outages due to natural shocks are found to last significantly longer than those due to non-natural shocks in—e.g. more than 4.5 times in Europe. Reasons include the challenge of locating wide-spread damages, and the sustained duration of storms. (3) Several factors can reinforce the adverse effect of natural shocks on power supply. In the US, forest cover is shown to significantly increase the risk of power outages when storms occur. (4) There are significant differences in network fragility. For instance, wind speeds above 35 km/h are found to be 12 times more likely to cause an outage in Bangladesh than in the US. This difference may be explained by a range of factors, including investments in infrastructure resilience and maintenance.

Candle in the wind?
Energy system resilience to natural shocks

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1. Introduction

After leaving behind a trail of destruction in the Caribbean, Hurricane Sandy struck New York on 29th October 2012. There, the storm claimed the lives of 53 people, destroyed thousands of buildings, and caused severe disruptions of public infrastructure, including water supply, transportation, and electricity. By some estimates over 2 million customers experienced power outages in the aftermath of the storm.

Just few years earlier, in 2007, Bangladesh was hit by one of the most powerful storms the country ever experienced. Cyclone Sidr formed in the central Bay of Bengal, and quickly strengthened to reach sustained wind speeds of over 260 km/h. The storm hit Bangladesh on November 15th 2007 and caused the deaths of around 3,400 people, according to the Government of Bangladesh (2008). The cyclone also led to one of the largest blackouts ever recorded: 75 million people lost access to power, which translated into 1.9 billion customer-hours of lost electricity services (Rhodium Group, 2018).

These experiences underline – not only the vulnerability of densely populated coastal areas to natural shocks – but more specifically the vulnerability of key lifeline infrastructure. Even in high-income industrialized economies electricity infrastructure can be heavily affected by natural shocks. Moreover, the data presented in this study show that the power outage due to Hurricane Sandy and Cyclone Sidr was by no means an isolated incident. Natural hazards are indeed the most frequent cause of electricity supply disruptions in the US, and the second most important cause in Europe. In contrast, in Bangladesh natural shocks account for a far smaller share of power outages – not because energy systems are more resilient, but because system failures and non-natural factors are so frequent that energy users experience daily outages. In other words, a fragile system is vulnerable not only to natural shocks, but also to a host of other stressors and shocks that include unmet demand, equipment failure, and accidents.

The 28 countries considered in this study cover about 1 billion people, and a wide range of geographies and climatic zone. [1] The US electricity network for instance consists of 275,000 km of high voltage transmission lines (>200 kV), almost 10 million km of low-voltage transmission lines, covering climatic zones from the Subarctic to the Subtropics, and serving over 325 million people (IEA, 2014). This means that its network elements – from generation to transmission and distribution – are exposed to a wide range of natural hazards, including tropical cyclones, tornados, wildfires, floods, winter storms, and droughts. The network is particularly dense in the Western mainland USA, a region that is frequently affected by storms – and outages.

In international comparison the USA have a high-quality electricity supply system. The electricity reliability index by the World Economic Forum (WEF, 2018) assess the risk of electricity supply interruptions and voltage fluctuations. According to this index, the United States ranked 26th in 2018 with a score of 6.2 on a scale from 1 (not reliable at all) to 7 (extremely reliable), out of 137 countries included in the study. While the US – expectedly – offers more reliable power supply than most developing countries, it ranks behind many of the developed economies in Europe considered in this study – such as France, the Netherlands, or Norway, which all score 6.8 or higher. This suggests that power supply interruptions are more common in the US than in other developed economies. The rest of this study will show that natural shocks (such as storms) are a key driver of these power supply interruptions.

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[1] This includes about 950 billion electricity end-users, considering a 75% electrification rate in Bangladesh.

Figure 1.1: USA electricity grid.
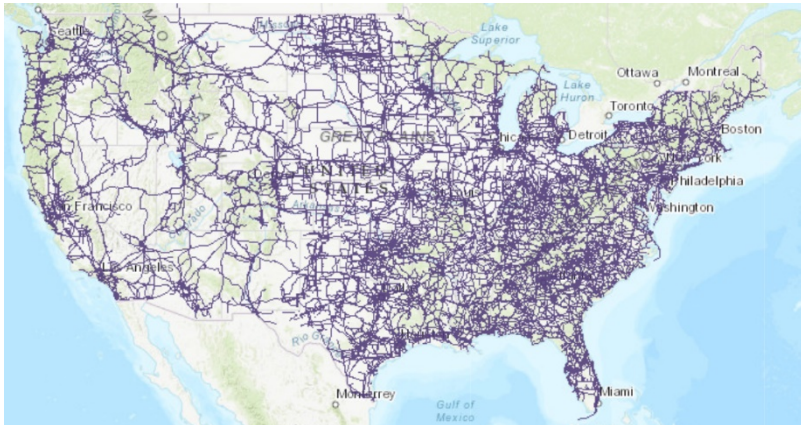
Figure 1.2: Left: Power outage in Lower Manhattan following Hurricane Sandy in Oct. 2012.[3] Right: Electricity reliability index for the USA (red), Bangladesh (green), and 135 other countries.
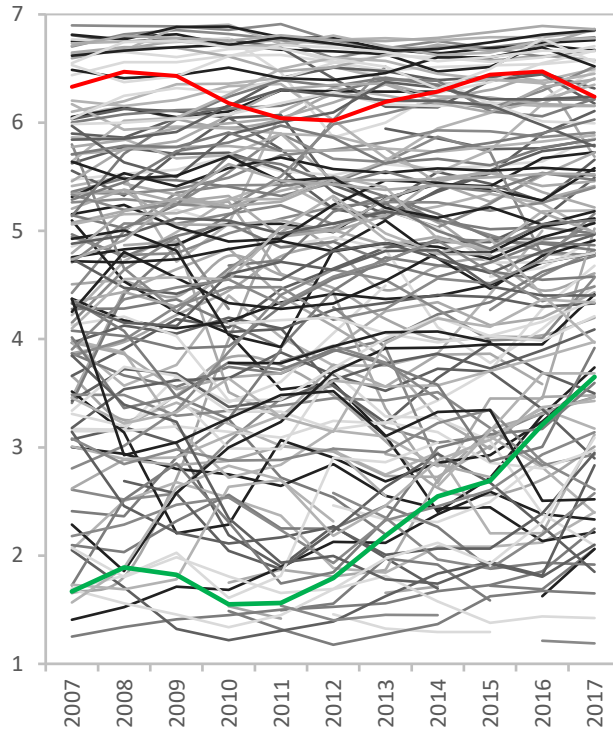
Note: The index assesses the lack of electricity supply interruptions and voltage fluctuations (1 = not reliable at all; 7 = extremely reliable). Source: (WEF, 2018)

This paper analyses 2,169 power outage events recorded by the US Department of Energy (2018), 463 outages recorded by the European Network of Transmission System Operators for Electricity[4] (European Commission, 2018), and 562 outage events recorded by the Bangladesh Rural Electrification Board[5].The US outages are recorded for all federal states of the USA and Puerto Rico, and they cover the years 2000 to 2017. In Europe, reports are issued in 26 countries and cover the period 2010 to 2016. In Bangladesh, the recorded outages are limited to those that were caused by storms in the period from 2000 to 2017, since no complete index of all outages exists.

The rest of this study is structured as follows. Section 2 provides an overview of power outage data in the US, in Europe and in Bangladesh as well as details on climate data. Section 3 describes power outage patterns in the three considered regions, with a focus on their frequency, regional distribution, and type of causes (Section 3.1), as well as the duration of different types of outages (Section 3.2). Section 4 provides an analysis of the drivers of outages and compares the vulnerability of the US and Bangladeshi networks to climatic events (Section 4.3).

2. Data

2.1. Power outages

2.1.1. USA

Detailed data on power outage events in the US are provided by the Office of Cyber-security, Energy Security, and Emergency Response at the US Department of Energy (2018). These electric emergency incidents and disturbances are recorded since the years 2000 and cover all federal states of the US, in addition to Puerto Rico and cross-border outages affecting Canada. Furthermore, the dataset details the location, the start and end date and time, as well as the cause of the power outage. In addition, the number of affected customers is reported, though unknown in about a third of the cases. The database records a total of 2,169 power outage events between 2000 and 2017. In cases when the start and/or end date of an outage event is not recorded the outage duration cannot be inferred – thus these observations are dropped from the sample for all analyses pertaining to outage durations.

The US dataset identifies 130 unique causes of power outages, and a majority of outages record combinations of multiple causes. These causes can be categorized into natural shocks and non-natural causes. For 19 outage events the causes are unknown. Natural shocks fall into six main categories: Storms, severe weather, extreme temperature, wild fire, flooding, and other. Non-natural causes include operational and technical disruptions, including planned load-shedding and un-planned technical failures, as well as external shocks such as vandalism or fuel supply shortages.

2.1.2. Europe

The European Network of Transmission System Operators for Electricity reports significant outages that occurred during the period 2000-2016 in the 26 countries of the Council of European Energy Regulators (European Commission, 2018). A *significant disruption* is defined as (1) causing a long disruption –typically

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[4] The data was retrieved from https://www.entsoe.eu/data/power-stats/
[5] Data was collected by the Bangladesh Rural Electrification Board (http://www.reb.gov.bd/).

three minutes or longer[6]– and (2) resulting in consumers being out of power.[7] Netherlands reports all disruptions of at least 5 seconds, and Cyprus and Malta do not have a classification. Countries included in the dataset represent the EU-28 (without Hungary, Denmark, and Bulgaria) plus Serbia.

The 463 significant outages are grouped in 128 unique categories detailing the causes of the disruption. We label each of these categories as natural shocks, non-natural causes, load-shedding, or other. Non-natural causes include technical problems on both supply and consumer sides as well as human error. Unlike in the US, vandalism on the electricity grid and fuel supply shortages play subordinate roles and thus are not reported as individual categories.

2.1.3. Bangladesh

The Bangladesh Rural Electrification Board (BREB) has recorded daily reports of division-level load shedding volumes since at least November 2009. Processing these daily reports is challenging as they are published as individual pdf scans of a non-harmonized form sheet with a layout that changes over the years. These scans have been converted into readable datafiles, from which daily division-level load shedding volumes were extracted through an automated text processing algorithm. The robustness of the resulting time series has been tested through manual comparison with the original form sheets. The load shedding volumes for divisions Chittagong, Rajshahi, Rangpur, Sylhet and Barisal have been found to be robust. However, given the lack of power outage data in Barisal, we exclude this division from the analysis. The remaining data is summarized in Figure 3.6 in annual aggregates.

Moreover, data on storm-induced outages are retrieved from daily records published at the district level by the Bangladesh Rural Electrification Board. The data reports outages that can be attributed to climatic shocks – in particular storms – during the period 2010-2017. The BREB publishes reports for 64 of its 79 power supply or Palli Biduyt Samity (PBS) zones[8]. However, due to heterogeneous reporting methods[9] and missing time stamps, we only used 28 PBS zones, distributed across 7 Bangladeshi divisions.[10] Therefore, estimates should be considered as lower bounds and conclusions taken as insights rather than a representative picture of the impact of storms on power outages in Bangladesh. A list of included districts and corresponding divisions may be found in the appendix (Appendix 4).

2.2. Climate data
2.2.1. ERA5 climate data for the US

To assess the storm exposure of Puerto Rico and all federal states of the USA, 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).[11] As the dataset goes back as far as 1950, wind speed and temperature data could be extracted for all recorded outage events since 2000, and for all 52 centroid coordinates of the respective US states and territories.

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[6] Therefore, we only keep the outages falling within the scope of this definition. Twenty-five outages whose duration is unknown are included in the dataset.

[7] The European Commission reports do not allow us to cross-check the number of consumers being out of power.

[8] Details on zones can be found in maps posted by the BREB Directorate at: http://gis.brebms.com/.

[9] Some reports only display yearly aggregates, preventing the matching of outages with climatic events.

[10] On 14 September 2015, Mymensingh Division was added as eighth division of Bangladesh. Given the time frame of the data, Mymensingh will be considered as a part of Dhaka division in the present analysis.

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

More specifically, wind data is obtained at a six-hour frequency since 2000 for all 52 locations in the US, thus yielding 1.55 million data points. 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 across all states and years. In the US, this threshold corresponds to about 40 km/h, which corresponds to the lower bound of a level 6 storm on the Beaufort scale. This approach implies that storms are defined at the national level, and certain states with consistently high wind speeds are strongly represented in the analysis. As a robustness check, Appendix 4 offers results for a state-specific storm specification that uses a state level wind speed distribution, instead of the national level wind speed distribution. 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, temperature data is obtained at midday with a 24-hour frequency since 2000 for all subnational locations. In line with the approach taken for wind speeds, a heat hazard is defined by counting days on which the midday temperature simultaneously exceeds 20 degrees Celsius and the 99.5th percentile of the state-specific temperature distribution since 2000.

2.2.2. Climate data for Bangladesh

Climatic hazards in Bangladesh are governed by the monsoon season from July to September. Tropical cyclones occur at the tail ends of the monsoon season. In addition, Severe Local Convective Storms (SLCS) occur in the pre-monsoon season in April and May, and are characterized by localized short and intense thunderstorms – known in Bangladesh as Nor'wester or Kalbaisakhi. We combine two sources of data to capture these distinct events: (i) ERA5 climate data, and (ii) lightning data based on NASA's Tropical Rainfall Measuring Mission Lightning Imaging Sensor (LIS).

ERA5 climate data for Bangladesh

During the monsoon season, which starts in June and peaks in August, the country experiences high temperatures and precipitation, as well as increased average wind speeds (Figure 2.1). In order to measure these phenomena, climate data is retrieved from the 5th global reanalysis (ERA5) conducted by the ECMWF[12]. We retrieve precipitation, temperature and wind speed data for the centroids of all seven divisions of Bangladesh from the ERA5 database. Daily climatic data correspond to the maximum daily value recorded at these locations.

The data, presented in Figure 2.1, show that average temperatures start to rise at the beginning of April and reach a maximum of about 30°C in May. The climate data captures high average wind speeds and high precipitation during the period July to September, which coincide with the monsoon season. Tropical cyclones are also captured in the data, though their intensity is underrepresented (Hodges *et al.*, 2017).

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[12] See analysis conducted in the US for further details on the model and structure of the data (section 2.2.1.).

Figure 2.1: Left: Wind diagram for Bangladesh; Right: Climate diagrams for Dhaka: Seasonality governed by the monsoon (2000-2017).
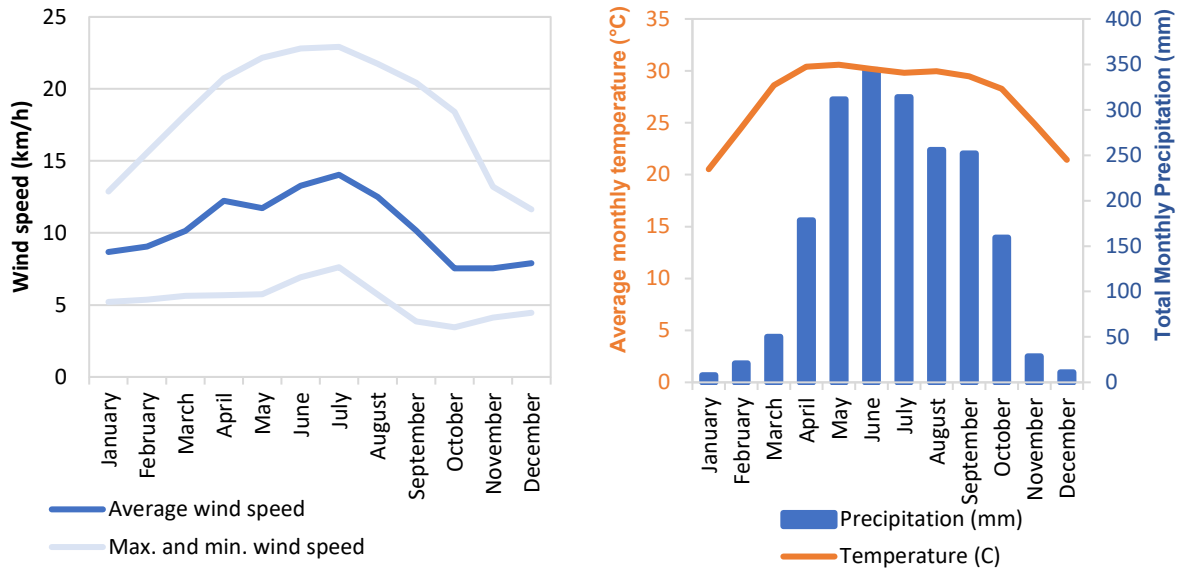
Source: authors based on ERA5 data Note: All values represent averages over the period 2000-2017.

Lightning data from the NASA Lightning Imaging Sensor (LIS).

Nor'westers – a type of Severe Local Convective Storms (SLCS) – occur in Bangladesh between April and May, when humidity and temperatures rise. They are the South Asian equivalent of Derecho events in the USA[13]. They cause considerable damage to assets and livelihoods as they result in short, intense, and very localized thunderstorms, combined with lightning and strong wind gusts. They are known in Bangladesh as Kalbaisakhi – which translates roughly to "evil summer". By reviewing thousands of local newspaper reports, Yamane et al. (2010) compile a database of 2,324 SLCS events covering the years 1990 to 2005. Their data illustrates the strong seasonality of SLCS, the majority of which are concentrated in April and May (Figure 2.2).

While Yamane *et al.* (2010) provide a clear picture of the seasonality of SLCS, their data does not cover the relevant period up to 2017. However, ERA5 climate data is not well suited to capture short, intense, and very localized storms, not least since wind speeds over 50 km/h cannot be reflected due to model restrictions and methodology. While the variance of ERA5 based wind speeds increases significantly in April, average wind speed from ERA5 do not capture well Nor'wester storms. Monthly average wind speeds do not peak during the Nor'wester season (Figure 2.1 (Left)).

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[13] https://www.spc.noaa.gov/misc/AbtDerechos/derechofacts.html

Figure 2.2: Left: Seasonal frequency of severe convective local storms (SLCS) from 1990 to 2005. Right: Average monthly number of lightning flashes from 1998 to 2014
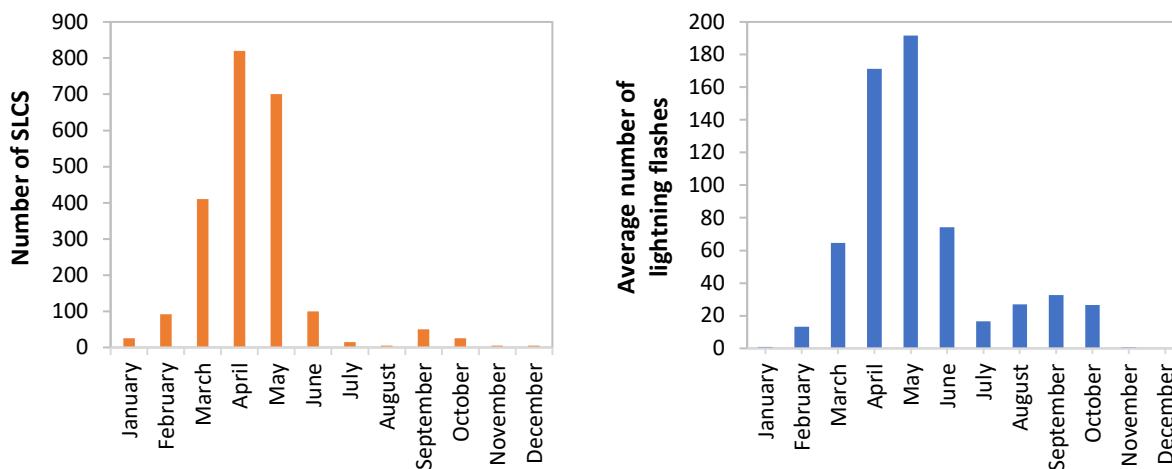
Source: Left : Yamane et al. (2010) ; Right: NASA Tropical Rainfall Measuring Mission Lightning Imaging Sensor (LIS) and Dewan et al. (2017)

In order to better capture SLCS, we use lightning data as a proxy. Lightning data are constructed by Dewan et al. (2017), who use data NASA's Tropical Rainfall Measuring Mission Lightning Imaging Sensor (LIS) from 1998 to 2014. This dataset provides estimated counts of lightning strikes. The LIS is a measurement device launched in 1997 to record lightning flashes between 35° N and 35° S latitude. With a spatial resolution of 4–7 km, LIS captures total flash counts, including both cloud-to-cloud and cloud-to-ground lightning flashes. The LIS is also well suited for identifying the spatial distribution of lightning, recording the time of events and measuring the radiant energy of lightning flashes (Dewan et al., 2017). They analyze lightning flash counts to examine annual, monthly and diurnal patterns of flash activity in Bangladesh over the study period (1998–2014). Overall, a total of 83,641 flashes were estimated to have occurred within the territory of Bangladesh, of which 86% occurred over land and the rest was over the Bay of Bengal. Figure 2.2 demonstrates that the seasonality of SLCS and lightning strikes is indeed strongly correlated.

2.3. Control variables

In addition to the climate and outage data, the analysis also includes auxiliary state-level control variables, in particular GDP per capita, annual power generation, the number of electricity customer accounts, surface area, and forest coverage (as a share of the state's total area). In Bangladesh electrification rates are also taken into account. The data is obtained from the World Bank's World Development Indicators (2018) and Hidden Dimensions of Poverty databases (Hansen *et al.*, 2013).

3. Outage patterns

Data from 28 countries enable an analysis of the trends and main causes of power outages. This section shows that the vulnerability of electricity systems to natural shocks varies significantly across countries. The share of overall outages that is caused by natural shocks typically lies anywhere between 10% and 70%, though subnational disaggregation (e.g. by federal states of the USA) yields an even wider range. Figure 3.2 summarizes these results and shows that natural shocks are indeed a significant (and often

leading) source of power supply disruptions in most of the 28 countries and 53 subnational jurisdictions considered in this study. The figure also demonstrates that the vulnerability of power systems to natural shocks is not simply explained by the income status of a country – lower income countries are not necessarily more or less vulnerable to natural shocks. Instead, network vulnerability depends on a variety of factors, including network density, vegetation, and maintenance practices.

Figure 3.2: Power outages due to natural shocks and GDP per capita.
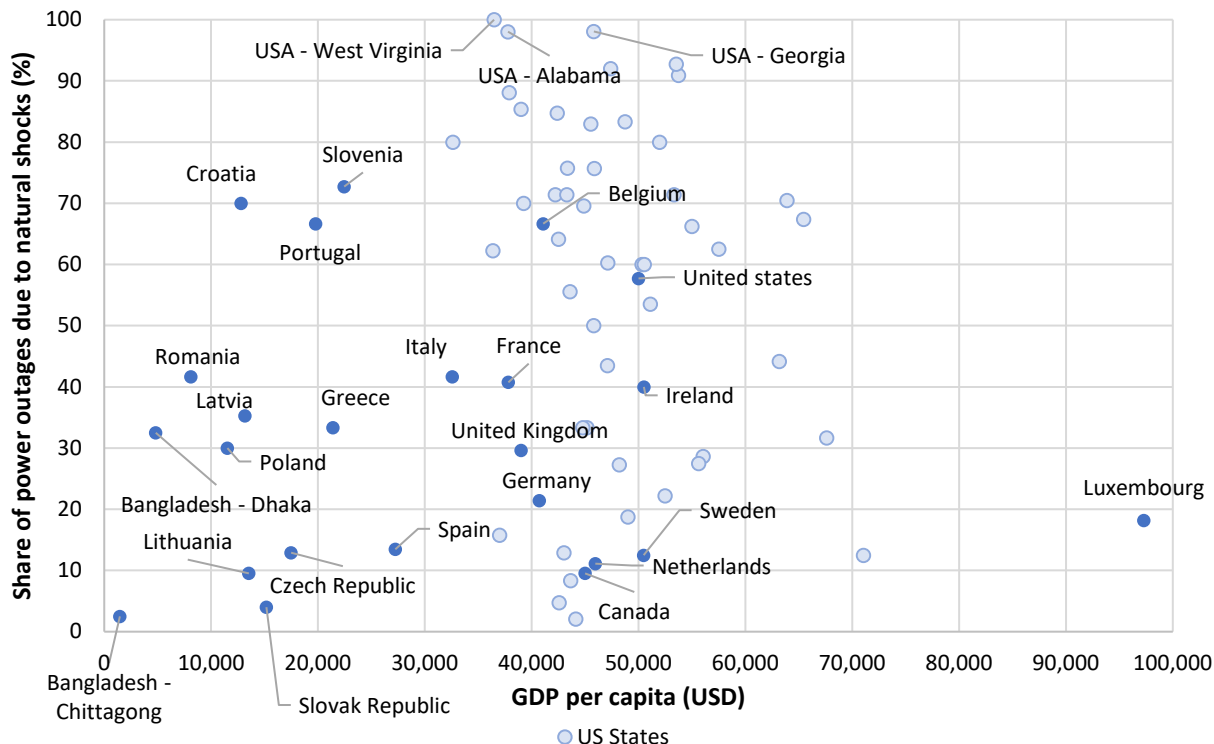
Source: authors. Note: Only cross-border outages are reported in Canada.

3.1. Outage frequency

3.1.1. Power outages in the US and Europe

By distinguishing the different causes of power outages (see Section 2.1), this section shows that natural shocks are a leading driver of electricity disruptions. Natural shocks can be seen to be the predominant cause of power outages in the US between 2000 and 2010 (Figure 3.3). Since then there has been a slight decline in outages due to natural shocks, while vandalism has increased significantly. Overall, between 2000 and 2017, 54.8% of all recorded power outage events have been caused by natural shocks, and 44.2% by non-natural causes (26.9% if excluding vandalism).

Measured by annual outages per-capita, European electricity supply is significantly more resilient than in the US. Moreover, while the number of outages increased over time in the US, European outages have been trending downwards over the period 2010 to 2016. Our data confirms findings of the European Commission (2018) that uses national indicators to assess the electricity network quality in the EU. Average regional trends indicate that power outages decreased between 2010 and 2014, both in terms of

frequency and duration. Non-natural causes are the main driver of outages: they caused 55% of all more outages, compared to 27% due to natural shocks.

Figure 3.3: Left: Number of power outages by cause in the USA (top) and in Europe (bottom). Right: Total number of outages in the considered period in the USA (2000-2017, top) and in Europe (2010-2016, bottom).
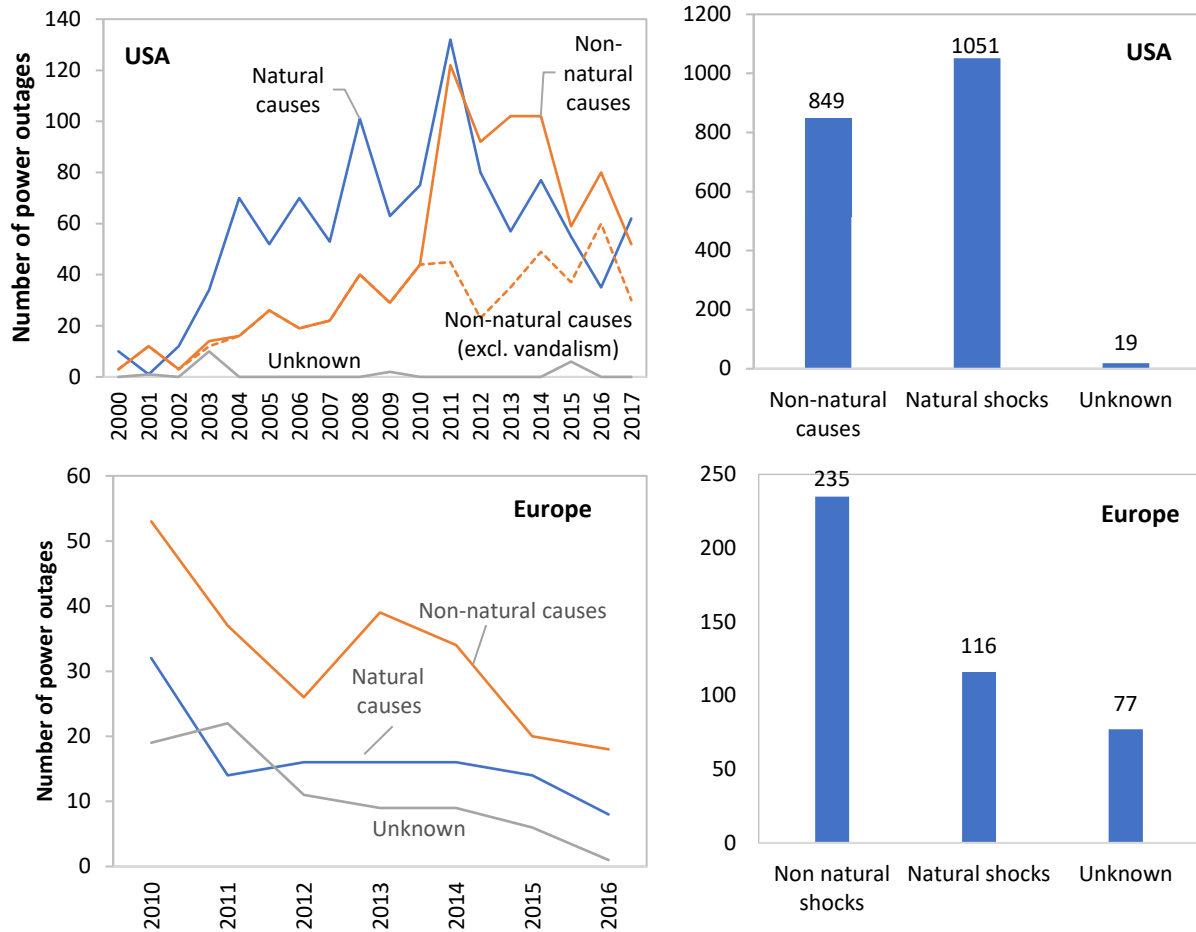
A disaggregation of hazard types in the USA shows that storms and severe weather events account for 92% of all natural shocks leading to outages (Figure 3.4).[14] "Severe weather" refers to a combination of storms, thunderstorms, or precipitation extremes. Storms alone account for 63% of natural shocks, and 34.5% of all power outages in the considered time frame. Other natural shocks, including wild fires, flooding, and extreme temperatures account for a relatively small fraction of overall outages, i.e. around 8% of all natural shocks, or 3.1% of all power outages. In Europe, the share of outages caused by natural shocks is about half of the USA, i.e. about 27%.

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[14] A similar analysis in Europe is not feasible due to lack of sufficiently disaggregated causes of outages.

Figure 3.4: Power outages in the USA caused by natural shocks: Disaggregation by hazard type.
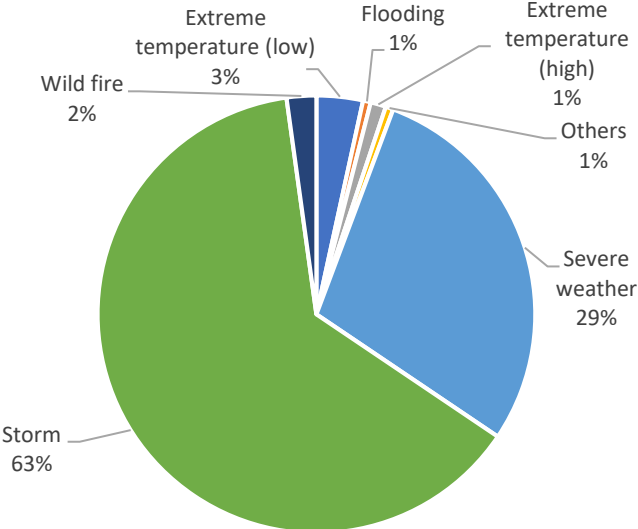
Regional disaggregation of the causes of power outages illustrates that there is large regional variation with respect to the predominant cause of power outages (Figure 3.5). In the US, while natural shocks account for the majority of outages at the national level, the state-specific share varies between 0% (in Montana) and 100% (in District of Columbia). In Europe, similar regional differences can be observed across countries. In France, natural shocks were responsible of 42% of all outages between 2000 and 2016, while Serbia did not report any outages due to natural shocks. This large variation is indicative of the wide range of drivers that determine the probability of outages, including the exposure to different types of natural hazards, environmental factors such as vegetation, the density of the grid, and regional differences in the quality of energy infrastructure.

Figure 3.5: Regional disaggregation of the causes of power outages in the US (top) and in Europe (bottom)
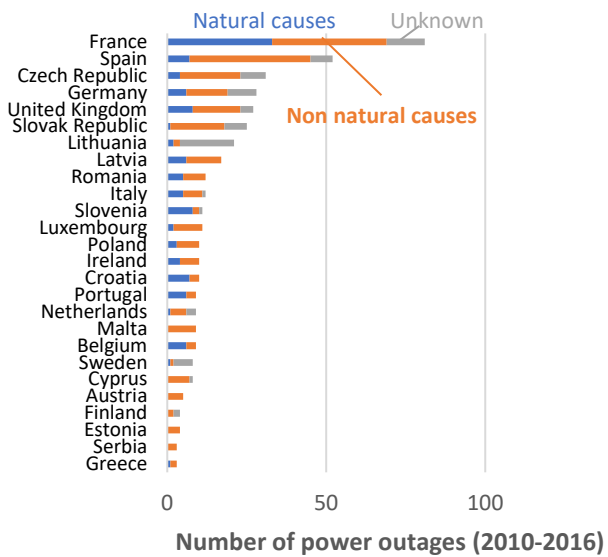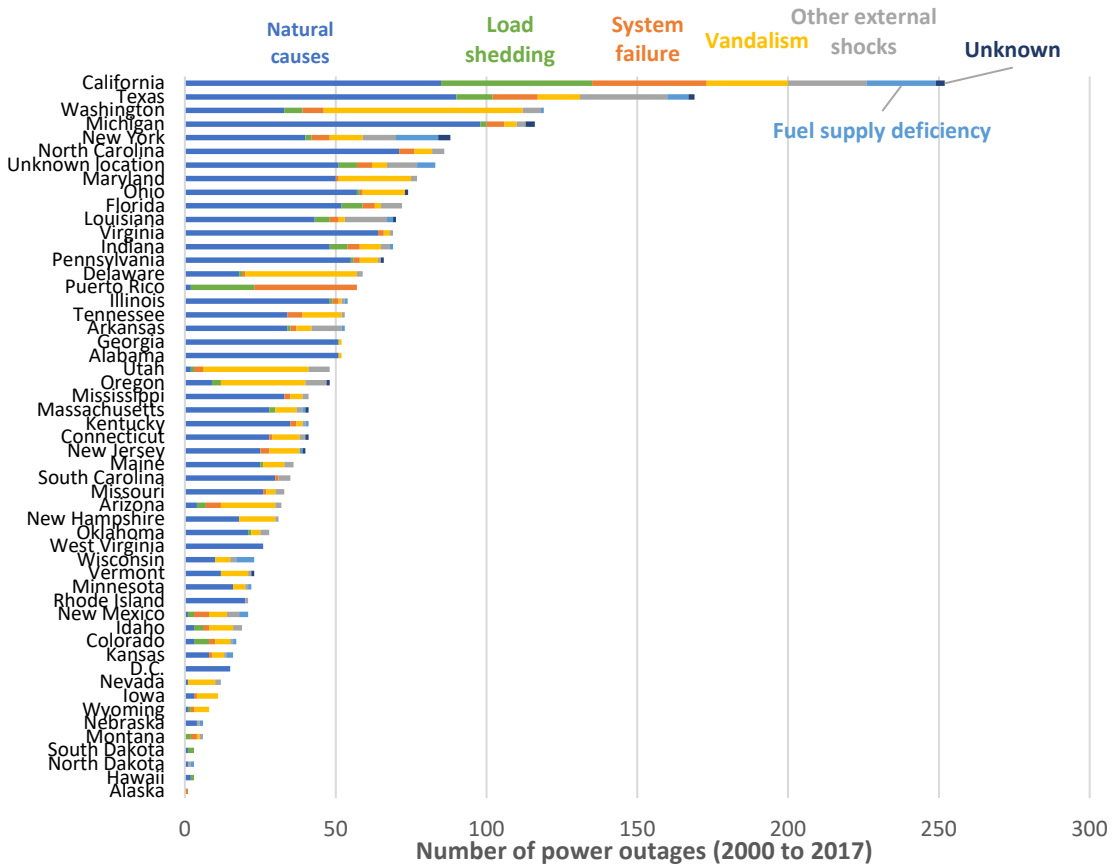
3.1.2. Power outages in Bangladesh

Load shedding volumes have decreased recently, thus suggesting improved network stability.
The Bangladesh Power Development Board (BPDB) is responsible for the planning, construction, and operation of power generation and transmission in the country. A key challenge for the BPDB is to meet energy demand during peak hours, and frequently resorts to load shedding (Islam and Khan, 2017). Load shedding is a common measure applied to avoid overloading the electricity network, employed by utilities when electricity demand exceeds supply to maintain voltage stability (Taylor, 1992). According to the *Sustainable Energy for All* initiative, 79 % of connected consumers in Bangladesh suffer power outages caused by regular load shedding.[15]

However, the WEF (2018) observes a considerable improvement in Bangladesh' electricity reliability index in the period between 2011 and 2017 (Figure 1.2). The information derived from daily BREB reports for the divisions Chittagong, Rajshahi, Rangpur, Khulna and Sylhet[16] suggest that load shedding is an almost daily occurrence in Bangladesh. But indeed, the data also show that over the period 2012-2016, the number of days with load shedding decreased continuously in all divisions, where data could be extracted (Figure 3.6). This can be interpreted as a sign of a more efficient power system, as power generation is aligned more accurately with electricity demand.

Figure 3.6: Decrease of the number of load shedding events and increase of the number of days of power outages caused by storms

Source: authors based on BREB data
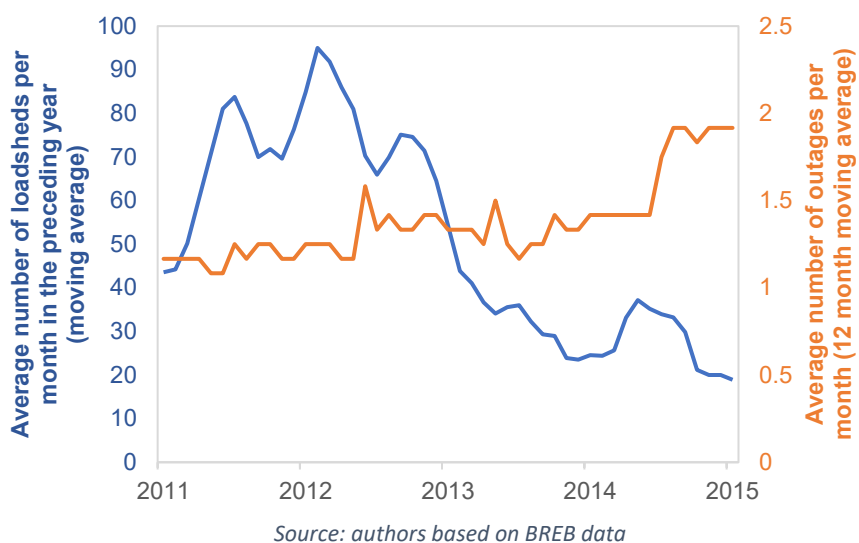
Storm related power outages are not decreasing during the same time frame.
While falling load shedding volumes suggest that the reliability of power supply has improved overall, resilience to natural shocks has not. During the same time period, storm-induced outages have been stable or even increasing in frequency – at the country level, and in all divisions where data is available (Figure 3.6). Over the period 2000-2017, outages were reported on 575 storm days. Bangladesh

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[15] "Sustainable electricity for all" initiative: SE4ALL database, IEA and World Bank
[16] Storm-related outages are not available in Barisal. Load-shedding data in Dhaka did not pass robustness checks. Therefore, those divisions were excluded from the comparison between load shedding and storm-related power outages.

experiences an average of 424 storm-induced outages per year, lasting 40 hours and affecting 13,500 consumers on average.

What share of outages are caused by natural hazards?

Unlike in the US, data on overall outages is not readily available for Bangladesh. One reason for this is that outages are occurring at such a high frequency that does not allow for reliable monitoring. For instance, the 2013 Enterprise Survey for Bangladesh suggests that the majority of firms experience more than two outages per day.[17]

In order to get a sense of the relative importance of storms as a cause of outages, we retrieve firm-level outage data from the Enterprise Surveys for 2007 and 2013. The survey covers six Bangladeshi divisions – Chittagong, Dhaka, Rajshahi, Khulna, Barisal, and Sylhet– and is representative at the country level. However, to ensure comparability with the BREB dataset, we illustrate the share of outages caused by storms for two selected divisions: Chittagong and Dhaka. Figure 3.7 compares the number of outages due to storms (as reported by BREB) with the average monthly number of all outages (reported in the Enterprise Surveys). In 2007, storms were responsible for approximately 1% of all outages in Chittagong and 24% in Dhaka. In 2013, those percentages increased in both regions: storms caused 4% of all outages in Chittagong and 41% in Dhaka.

Figure 3.7: Number of outage reports per month in Chittagong and Dhaka

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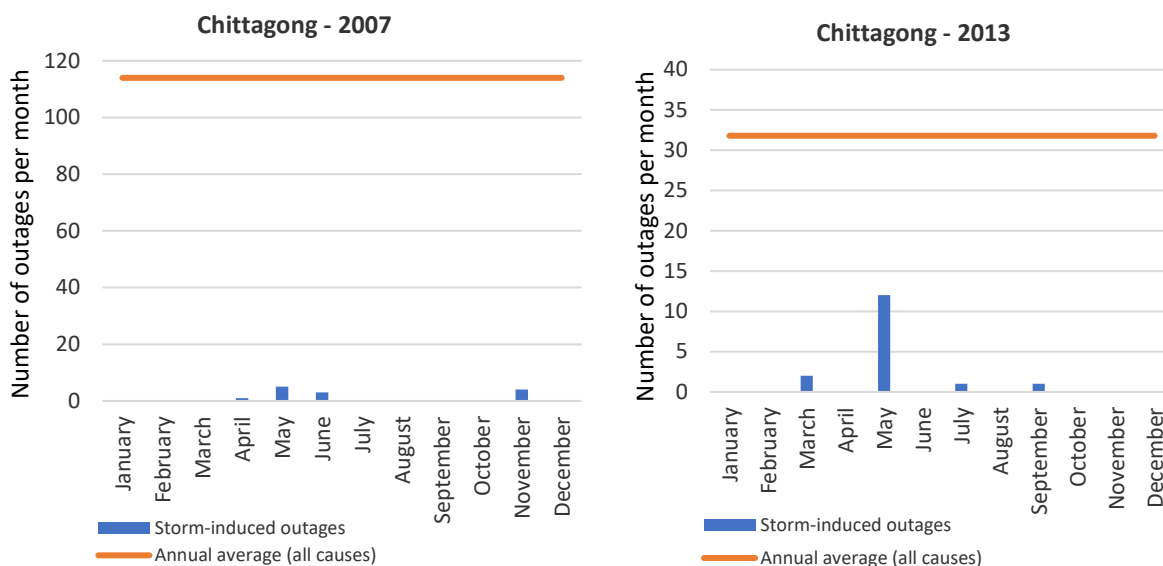
[17] Detailed figures may be found at:
http://www.enterprisesurveys.org/data/exploreeconomies/2013/bangladesh#infrastructure

Dhaka - 2007

Dhaka - 2013
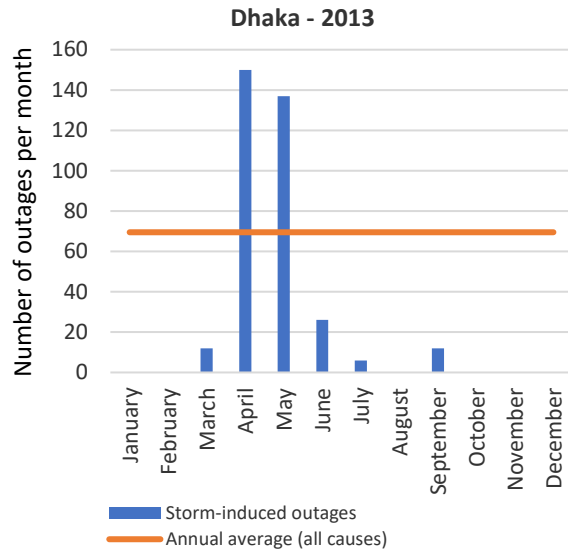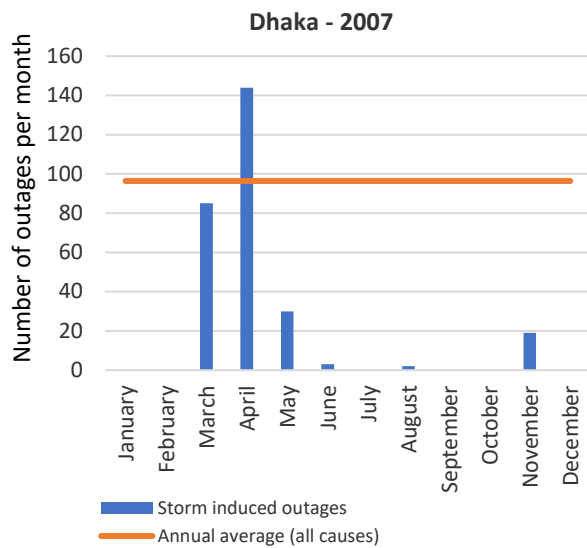
Source: authors based on BREB data and ES data

Overall these results provide two key insights. Firstly, the absolute frequency of outages is significantly larger than in developed countries studied earlier.[18] In particular, this is true for the number of outages caused by storms, providing evidence for relatively low resilience of Bangladeshi electricity supply. Secondly, the data indicates that the *share* of storm-induced power outages in Bangladesh is significantly *lower* than in the US or Europe – while increasing over time. This suggests that even for increasingly well-managed power systems natural shocks continue to pose a threat which grid operators struggle to deal with.

Spatial distribution of storm-induced power outages

The number of storm-induced power outages varies significantly across divisions. Figure 3.8 shows the disaggregation of power outage reports by the seven Bangladeshi divisions[19]. The majority of storms that induced outage during the period 2000-2017 were recorded in Dhaka, Chittagong and Rajshahi, while none are attributable to Barisal. The reason for missing data for Barisal is unclear. While we had to exclude several PBS Zones in Barisal due to reporting and date issues, it is unlikely that Barisal did indeed not experience any storm-related outages in the included zones. Anecdotal evidence – e.g. reported by local newspapers – suggests that Barisal did indeed experience storm-related outages in the period covered by the data.[20] Thus, this division is excluded in the rest of this study.

On average, he longest storm-induced outages are experienced by Rangpur's population while in Dhaka and Sylhet such disruptions are shorter but more frequent power disruptions: In other words, a storm in

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[18] The World Bank Doing Business measure for instance estimates that firms in the USA experience 0.5 power outages per year on average. In Bangladesh, no such number is reported –the Doing Business methodology does not report a number if outage frequency exceeds 100 times per year, as no accurate estimate is possible.[18] In other words, disruptions in the electricity network in Bangladesh are far more frequent than serious storms.

[19] The analysis that follows will be conducted at the division level, to accommodate the climate data.

[20] https://www.thedailystar.net/backpage/hailstorm-rain-take-country-unawares-660337

Dhaka and Sylhet leads to multiple, relatively short power outages while Rangpur experience longer but fewer electricity disruptions. Outages in Dhaka tend to affect the largest number of consumers on average, which is explained by the high population density in this area[21].

Figure 3.8 displays a large difference between the number of days of outage and the number of outages. For example, in Dhaka, a storm seems to be causing on average 17 outages while in Chittagong, a storm is reported to be responsible for barely more than one power disruption. While this could be the sign of discrepancies between the quality of the grid at the division level, this difference could be due to reporting practices being inconsistent across districts and divisions. Therefore, it is important to bear in mind that the analysis is not meant to be representative at the country level. In what follows, we will favor the use of dated storms inducing outages when matching power disruptions with climate data, rather than the number of outages associated to each event. The magnitude of a blackout will be inferred from information on duration and number of consumers affected.

Figure 3.8: Spatial distribution of outages

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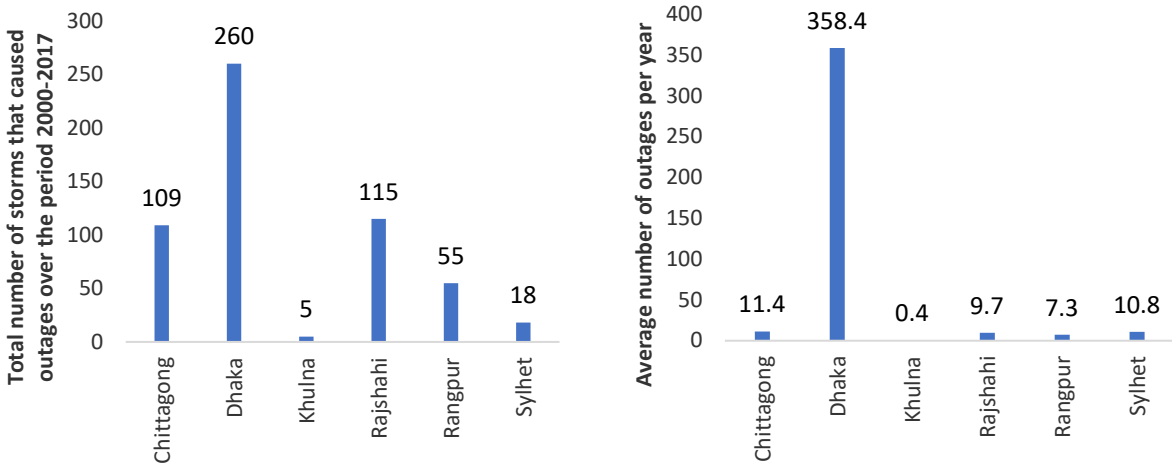
[21] For the purpose of validation, newspaper coverage was sought for outages having affected more than 1,000,000 people. When such evidence could not be found, those observations were excluded of the analysis. Overall, we deleted 13 outage reports, five of which were issued in Khulna.

Left chart:

Average number of people affected by outages per year (thousands)

250
208
200
150
99
100
62
50
22
24
33
0

Chittagong Dhaka Khulna Rajshahi Rangpur Sylhet

Right chart:

Average duration of outages (hours)

800
702
700
600
500
471
400
300
200
122
100
30
7
26
0

Chittagong Dhaka Khulna Rajshahi Rangpur Sylhet
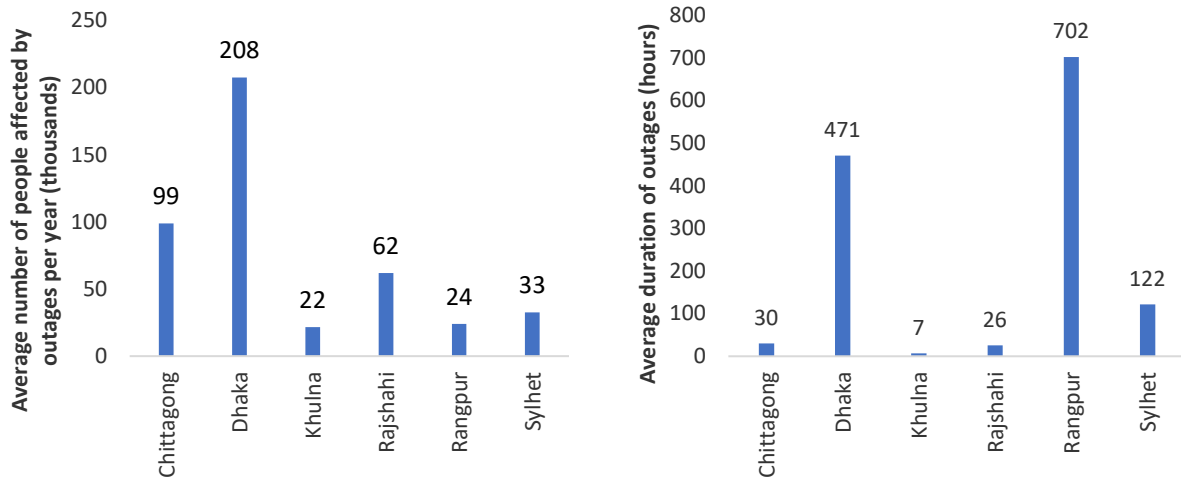
3.2. Outage duration in the US and Europe

The adverse impact of power outages on people and businesses is ultimately determined not only by their frequency, but also their duration. The over 2,000 power supply disruptions recorded by the US Department of Energy (2018) range in duration from a few seconds to several weeks. Long lasting outages can be particularly costly, as they require firms to adjust their production process, operate costly backup generation capacity, or invest in alternative energy sources. Firms in different sectors are likely to be affected to different extents, not least due to varying degrees of energy intensity of production (Allcott, Collard-Wexler and O'Connell, 2016; Ramachandran, Shah and Moss, 2018).

While Section 3.1.1 puts in evidence the important role of natural shocks in causing power outages in Europe and the US, the importance of natural shocks becomes even more evident when considering outage durations (Figure 3.9). In the US, power outages caused by natural shocks last on average 59 hours (or 2.4 days); this makes outages due to natural shocks more than twice as long as outages due to non-natural causes, and 6.5 times as long as outages due to load shedding. This means that 69% (or 5,636 hours, or 234 days) of the average annual outage duration between 2000 and 2017 in the US is caused by natural shocks while non-natural causes, including vandalism, are responsible for about 26% (or 2,143 hours, or 89 days) of the annual duration.

In Europe, the gap between climate-induced outages and other outages is even wider: on average, climate-induced outages last 9 hours, which is 4.5 times as long as outages caused by non-natural external causes and 9 times as long as load-shedding events. Annually, natural shocks are responsible for 54% of the average annual outage duration in the considered European countries.

Figure 3.9: Average duration of an outage and average annual outage duration (top) in the US (bottom) in Europe.
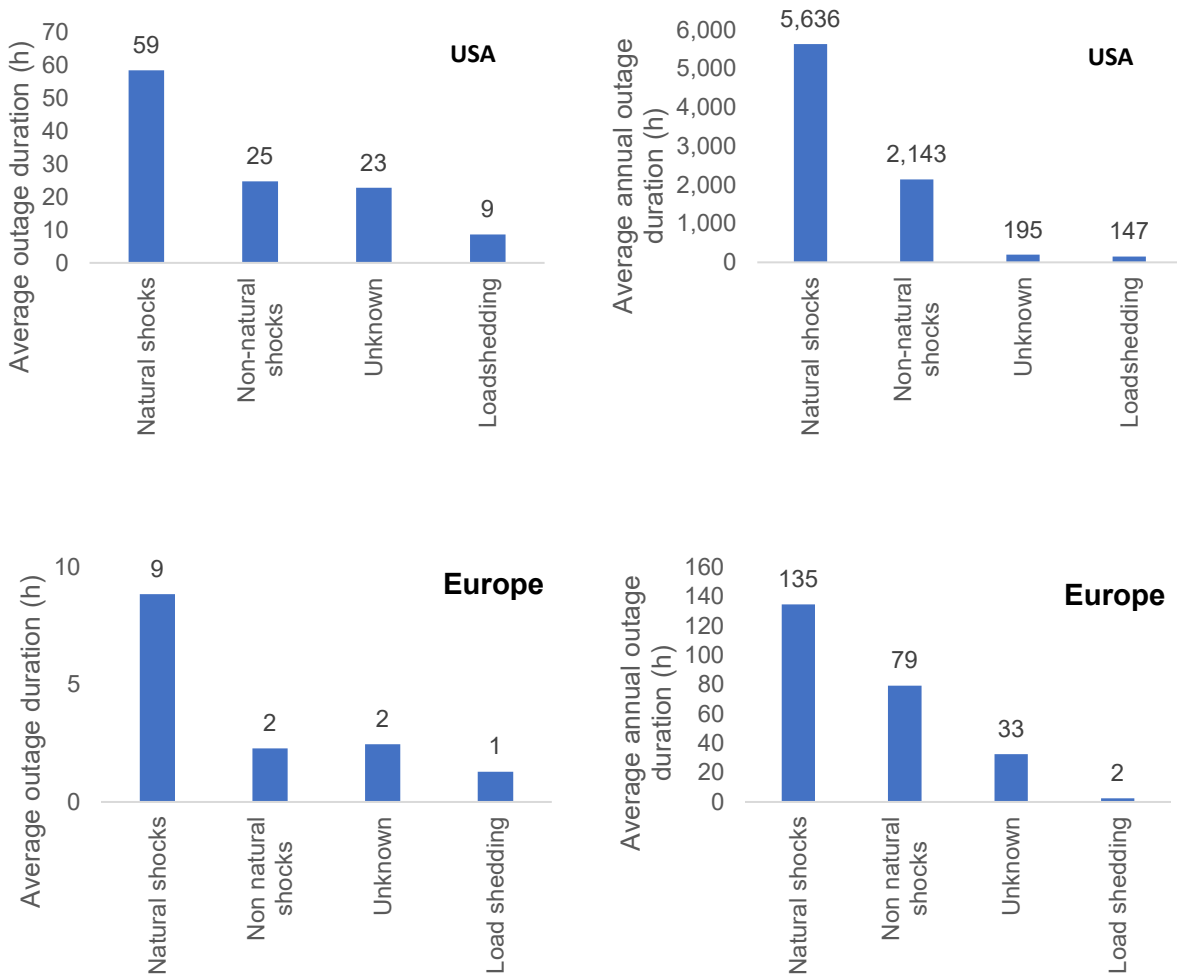
Source: authors. Averages are computed over 2000-2017 for the US and 2010-2016 for Europe.

Several factors may explain this pattern: natural shocks, such as storms, extreme temperatures, or wildfires, tend to affect large segments of the power network at once. This means that one natural shock can affect the power system in multiple – potentially unexpected – locations, some of which may be difficult to locate and access. For instance, as Section 4.1.1 shows, storms are particularly likely to cause outages in heavily forested areas. Falling trees and branches are among the most common cause of damages to electricity transmission lines following heavy storms. These damages tend to affect transmission lines along large distances, thus requiring extended periods for repairs. Moreover, natural shocks often have extended durations themselves thus preventing immediate fixing of damages to the system, e.g. hurricanes that last several days, or wildfires that cannot be controlled rapidly. In contrast, equipment failures or vandalism tends to occur in single locations, thus making immediate repairs easier.

Figure 3.10: Total annual outage duration by cause in the US (top) and in Europe (bottom)
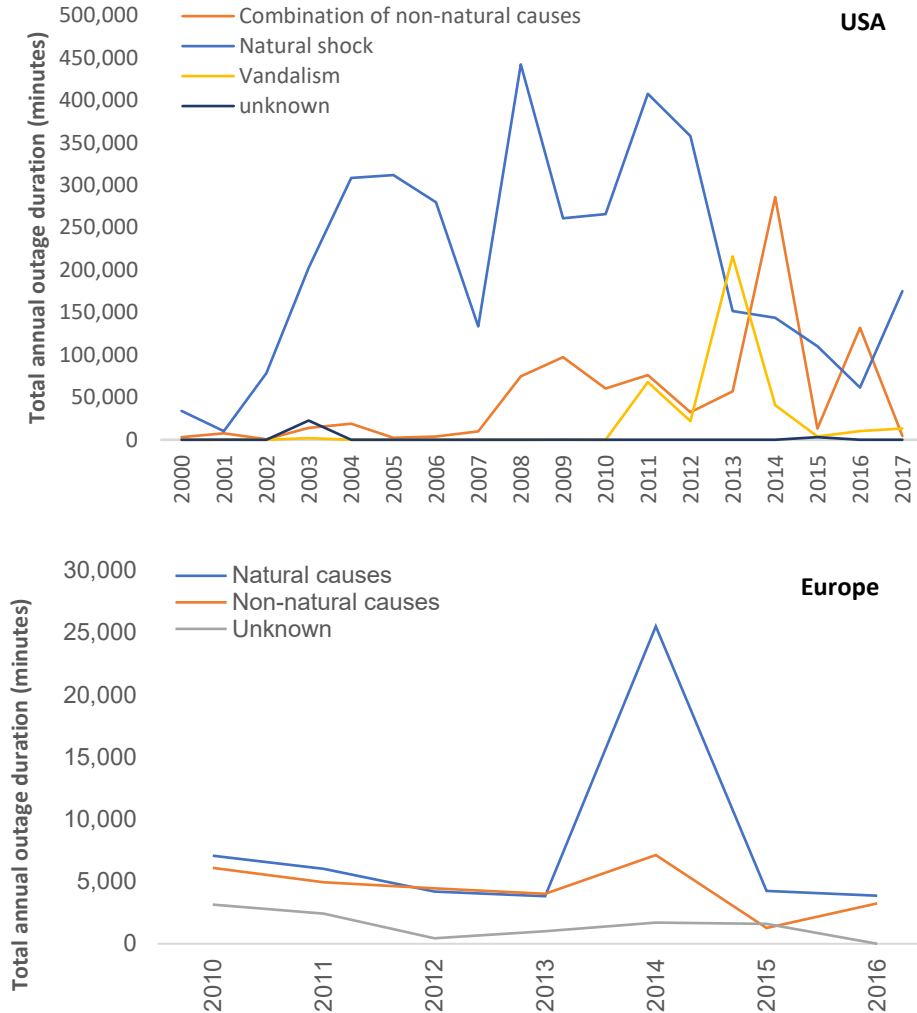
Source: authors. Note: The peak in duration of outages caused by climatic events in 2014 in Europe is driven by one particular event: an ice storm in Slovenia that left the country out of power for several days.

4. Drivers of outages: natural shocks and external factors

Previous sections have shown that natural hazards, and storms in particular, are the leading cause of power outages in developed economies and an important factor elsewhere. Naturally, reducing corresponding economic costs presupposes understanding of exposure risk and identification of resilience factors to be harnessed for policy design. For example, this section will show that differential exposure to storms alone cannot fully explain the distribution of storm-related power outages. To assess underlying mechanisms, this section empirically tests a range of external factors that may modify the vulnerability of the electricity grid.

4.1. Evidence from the US

For the purpose of this section, storms are defined as exceed the 99.5[th] percentile from all wind speed observations across all states and years (see Section 2.2).[22] This approach implies that storms are defined at the national level, and certain states with consistently high wind speeds are strongly represented in the analysis. As a robustness check, Appendix 4 offers results for a state-specific storm specification that uses a state level wind speed distribution, instead of the national level wind speed distribution.

In line with the approach taken for wind speeds, a heat hazard is defined by counting days on which the midday temperature simultaneously exceeds 20 degrees Celsius and the 99.5[th] percentile of the state-specific temperature distribution since 2000.

The first aim of this analysis is to empirically quantify the causal impact of storms on outages. Along the way, we test for the existence of adaptation effects, i.e. whether any given storm is less likely to result in a power outage in states that experience frequent storms (compared to states with relatively fewer storms). Secondly, the inclusion of controls and interaction effects allows to assess which external factors play a role in determining whether a storm does indeed result in a power outage.

4.1.1. Storms

Figure 4.1 shows, for each state and year, the number of storms (defined as the extreme events on a national wind speed distribution) and the total duration of power outages caused by storms. It is evident that – using these definitions – there is no apparent positive relationship: More storms do not automatically mean that a state experiences more power outages. The maps in Figure 4.2 illustrate this further. Most storms are recorded in the central USA along a relatively thinly populated North-South corridor – commonly known as the Tornado Alley. However, most storm-related power outages are recorded along the far more densely populated East and West Coasts as well as the Great Lakes region.

Figure 4.1: Storm frequency and actual electricity disruptions.
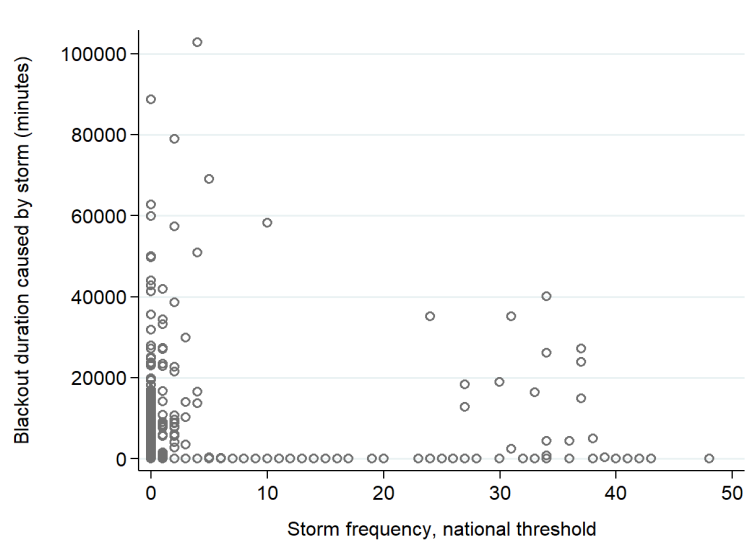
Note: Each circle represents a state-year. Source: Author's calculation.

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[22] We tested various percentiles, without much effect on qualitative conclusions.

Figure 4.2: Factors including storm exposure, forest and grid density, as well as adaption may all play a role in determining whether storms result in power outages.
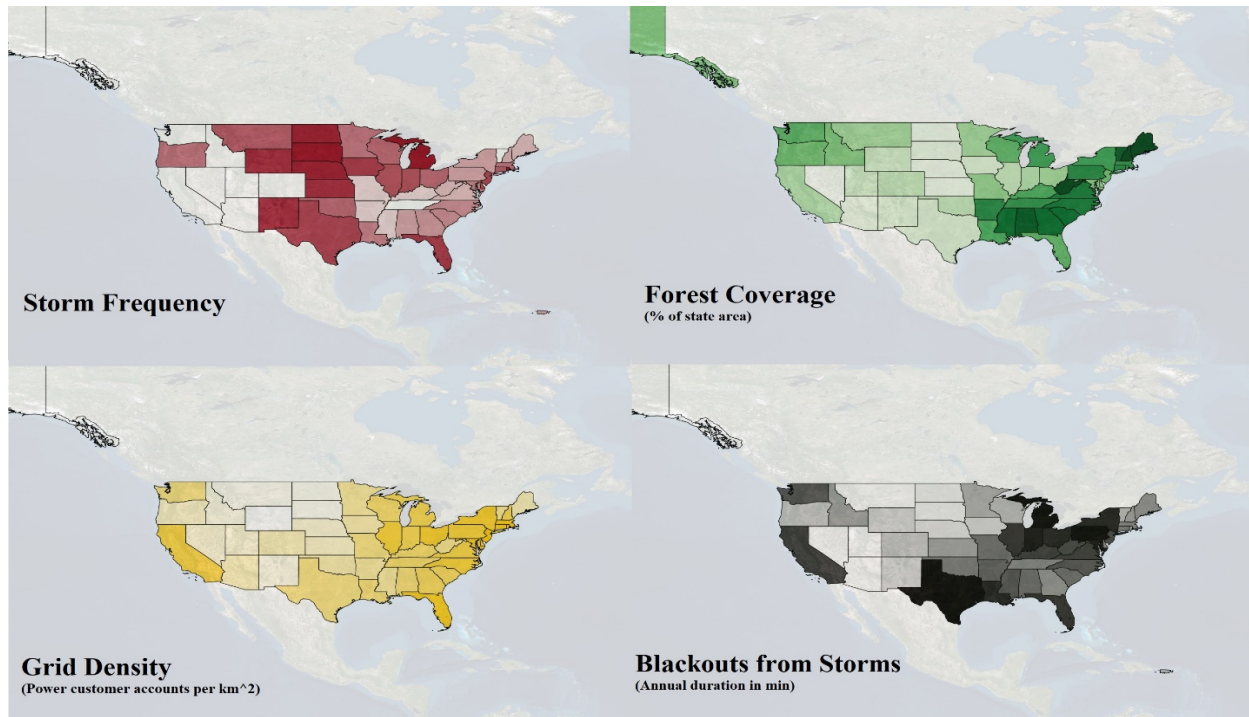
Source: The Hidden dimensions of poverty database (Hansen *et al.*, 2013), World Development Indicators (2018)*, US Energy Information Agency (2018) and author's calculation*

For a more systematic assessment, Table 4.1 presents the results for a pooled Ordinary Least Squares analysis with the step-wise addition of control variables and interaction terms. As illustrated in Figure 4.1, the single-variable specification in Column 1 shows that storm frequency alone is not significant in explaining the number of power outages caused by storms.

Column II presents results for a model specification that controls for grid density (defined as the number of customers connected to the power grid), network fragility (defined as the number of non-storm-related power outages, as an indicator of infrastructure quality), and forest density (defined as the share of the state's surface with forest cover). Forest density, more than grid density, emerges as an important driver of storm-related outages. Indeed, power outages due to storms are frequently caused by falling trees and branches that damage energy infrastructure.

However, adding an interaction term to the model (Column III), shows that storms are most prone to causing outages in states that have high forest coverage. For instance, in a state with about 50% forest coverage such as New York, one additional storm is associated with about 463 minutes of additional outage time.[23] In fact, the interaction of storms and forests is the single most important variable for explaining the variance of storm-related outages. When this interaction term is added, grid density also

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[23] For 100% forest coverage the additional outage time is 1,217 minutes, which is further reduced by 127 minutes due to an adaptation effect.

shows the expected sign, i.e. states with a large number of connected customers are recording more storm-related outages.

The model specification in Column III also suggests the presence of an adaptation effect: Grid operators learn and adapt to storm hazards, especially in states with high storm occurrence. Controlling for the interaction of storms and forest coverage, higher storm frequency itself tends to *reduce* blackout time. This learning effect is stronger where grids are denser. Controlling for other state and year specific characteristics leaves the overall conclusion unchanged (Column IV).

Table 4.1: Linking storm hazard and storm blackouts.

Storm blackouts, annual duration	(I)	(II)	(III)		(IV)	
Storm frequency	83.15	67.37	-127.05	***	12.44	
(national threshold)	(50.94)	(57.10)	(37.64)		(75.52)	
Grid density		13.77	25.73	**	26.45	*
(accounts per km²)		(8.40)	(9.31)		(10.91)	
Fragility		0.011	0.017		0.050	
(other blackouts per mio accounts)		(0.05)	(0.05)		(0.06)	
Forest coverage		2978.3 *	1342.4		2320.8	
(% of state area)		(1231.5)	(1183.2)		(1221.1)	
Storm frequency x			-3.430	***	-2.801	***
Grid density			(0.751)		(0.697)	
Storm frequency x			-0.0094		-0.0057	
Fragility			(0.0064)		(0.0056)	
Storm frequency x			1217.4	***	810.2	**
Forest coverage			(274.4)		(276.9)	
Power accounts					0.0431	
(in '000s)					(0.0002)	
Power generation					0.032	*
(annual, in MWh)					(0.013)	
GDP per capita					-1099.0	
(relative to US average)					(1922.0)	
Year fixed effects					YES	

Constant	3511.2	***	1992.4	***	2307.4	***	-3470.2
	(328.0)		(517.6)		(528.8)		(2125.1)
N (state-years)	911		882		882		833
R-squared	0.00		0.02		0.05		0.21

Note: Pooled OLS, standard errors clustered on state level, in parenthesis. Significance levels: *** 0.001, ** 0.01, * 0.05. Source: authors

4.1.2. Heat

Electricity grids are sensitive to heat for several reasons. Exceptionally hot days cause high electricity demand, especially due to an increase in air conditioning. Moreover, heat reduces the carrying capacity of electric transmission lines, thus further aggravating the effect of increased demand (Bartos et al., 2016). In line with the assessment above for storms, Table 4.2 presents the results of a pooled Ordinary Least Squares analysis with the step-wise addition of control variables and interaction terms. The single-variable specification (Column I) shows that one additional exceptionally hot day increases blackout time by almost 30 minutes, on average.

The model specification in Column II introduces three additional control variables: (i) Grid density, as a measure of how dense or spread out the transmission and distribution network of a state is, (ii) for network fragility, i.e. how disruption prone the network is when only considering non-natural external causes of outages, and (iii) the number of power accounts, as an indicator of the complexity of the system and magnitude of demand. In this specification, the additional blackout duration due to an exceptionally hot day remains stable from the single-variable specification. Moreover, the number of power accounts increases blackout duration with strong statistical significance.

The model specifications in Column III introduces an interaction term for the frequency of exceptionally hot days and the number of power accounts. For instance, in New York, with 8.2 million registered grid customers, an additional extreme heat day is associated with an additional 89 minutes of outage duration. As in the case of storms, there is a small adaptation effect, as states that experience hot days more frequently tend to experience fewer outage minutes. This result is robust to the introduction of further state and year level control variable.

Table 4.2: Linking heat frequency and blackouts across states and time

Heat blackouts, annual duration	(I)		(II)		(III)		(IV)	
Heat frequency	27.3	*	24.2	*	-25.6	**	-31.2	***
(Number of exceptionally hot days)	(14.6)		(13.9)		(12.7)		(10.2)	
Grid density			0.26		0.94		1.53	
(accounts per km^2)			(0.69)		(0.88)		(1.67)	
Fragility			-10.6		-14.3		420.0	

	(1)	(2)	(3)	(4)
(other blackouts per mio accounts)		(41.6)	(25.1)	(734.6)
Power accounts		0.046 ***	0.023 *	0.036
(in '000s)		(0.017)	(0.013)	(0.031)
Heat frequency x			-0.080	0.275
Grid density			(0.329)	(0.448)
Heat frequency x			6.4	-386.0 *
Fragility			(10.0)	(210.0)
Heat frequency x			0.014 ***	0.015 ***
Power accounts (in '000s)			(0.003)	(0.003)
Power generation				-6E-04
(annual, in MWh)				(0.0011)
GDP per capita				-126.3
(relative to US average)				(128.0)
Forest coverage				-225.6 *
(% of state area)				(130.9)
Year FE				YES
Constant	38.5 *	-89.8 *	-14.8	283.0
	(21.1)	(49.9)	(30.3)	(172.3)
N (state-years)	911	900	900	833
R-squared	0.00	0.03	0.04	0.07

*Note: Pooled OLS, standard errors clustered on state level in parenthesis. Significance levels: *** 0.01, ** 0.05, * 0.10. Source: authors*

4.2. Evidence from Bangladesh

This study also shows that the resilience of an energy system to natural shocks ultimately is closely associated with its overall stability and service reliability. Even in the absence of natural shocks, electricity consumers in Bangladesh are used to unreliable service. According to the 2012 Enterprise Survey conducted by the World Bank (World Bank, 2018), 73% of firms report experiencing regular power outages, with an outage frequency of 85 times per month and a duration of 70 minutes on average. In addition, a significant share of the population still does not have access to electricity. In 2016, about 76% of the Bangladeshi population were estimated to be connected to the grid, though access rates differ considerably across divisions (World Bank, 2016). The Household and Income Expenditure Survey conducted in 2010 by the Bangladesh Bureau of Statistics constitutes one of the few sources of sub-

nationally disaggregated electrification rates (Bangladesh Bureau of Statistics, 2010). It suggests that 90% of the urban population had access to electricity, compared to only 42% in rural areas.

Improving the reliability and availability of electricity services continues to be a key priority of the Government of Bangladesh. Indeed, the electricity reliability index by the World Economic Forum suggests that Bangladesh has made significant and continuous improvements in its electricity provision in the past 10 years (Figure 4.3). Nevertheless, frequent power outages are still the common symptom of a fragile energy system. Relatively low electrification rates in rural areas also imply that power outages are particularly prevalent in densely populated urban areas, including in Dhaka and Chittagong where electrification rates tend to be the highest (BREB data and Figure 4.3).

Figure 4.3: Left: Bangladesh electricity grid. Right: Electricity reliability index for Bangladesh (red) and 136 other countries.
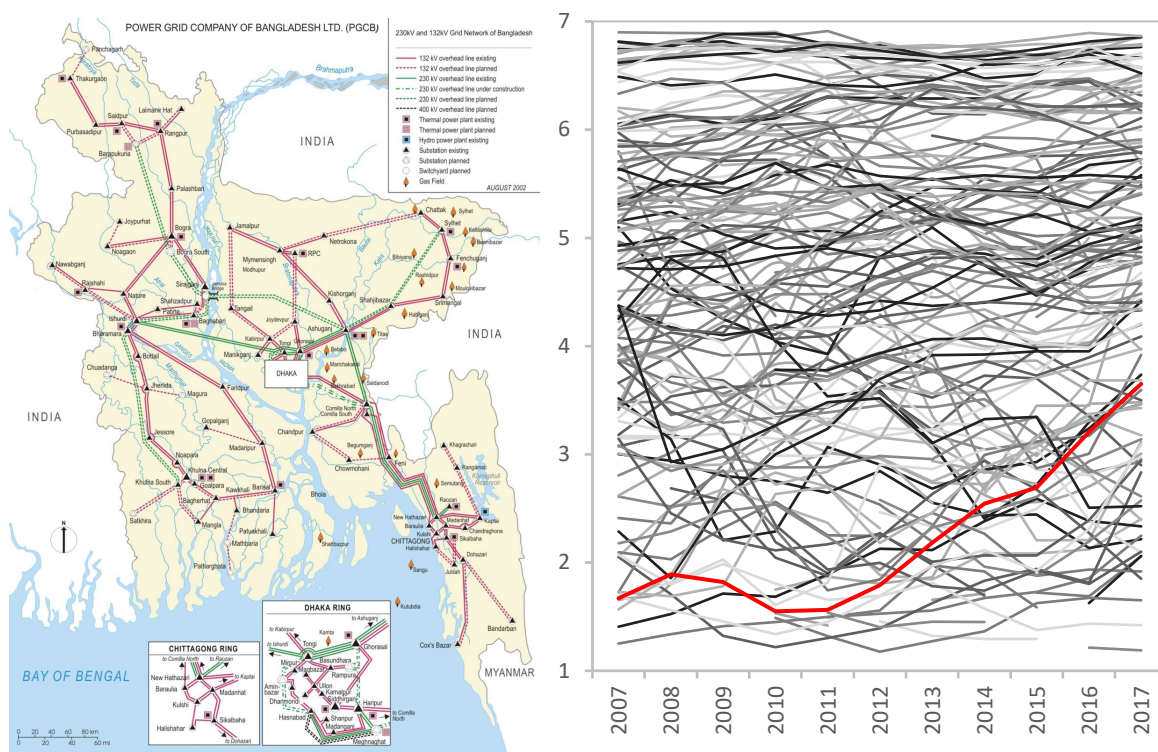
Note: The index assesses the lack of electricity supply interruptions and voltage fluctuations (1 = not reliable at all; 7 = extremely reliable). Source: (left) GENI Initiative. (right) WEF (2018).

Our data also shows that the majority of storm induced power outage in Bangladesh are indeed due to Nor'wester storms. In Bangladesh, 65% of the days with storm-induced outages were reported during the months of April and May. This pattern remains when considering the total outage durations or the number of affected people (Figure 4.4). The September spike for outage duration can be attributed to specific events that occurred during the monsoon season, during wind speeds are lower than in April and May, but are accompanied by sustained precipitation and floods. For instance, Rangpur experienced such events in September 2015 that caused outages lasting more than 30 days.

Figure 4.4: Outages frequency, duration, and impacts compared with average wind speeds.
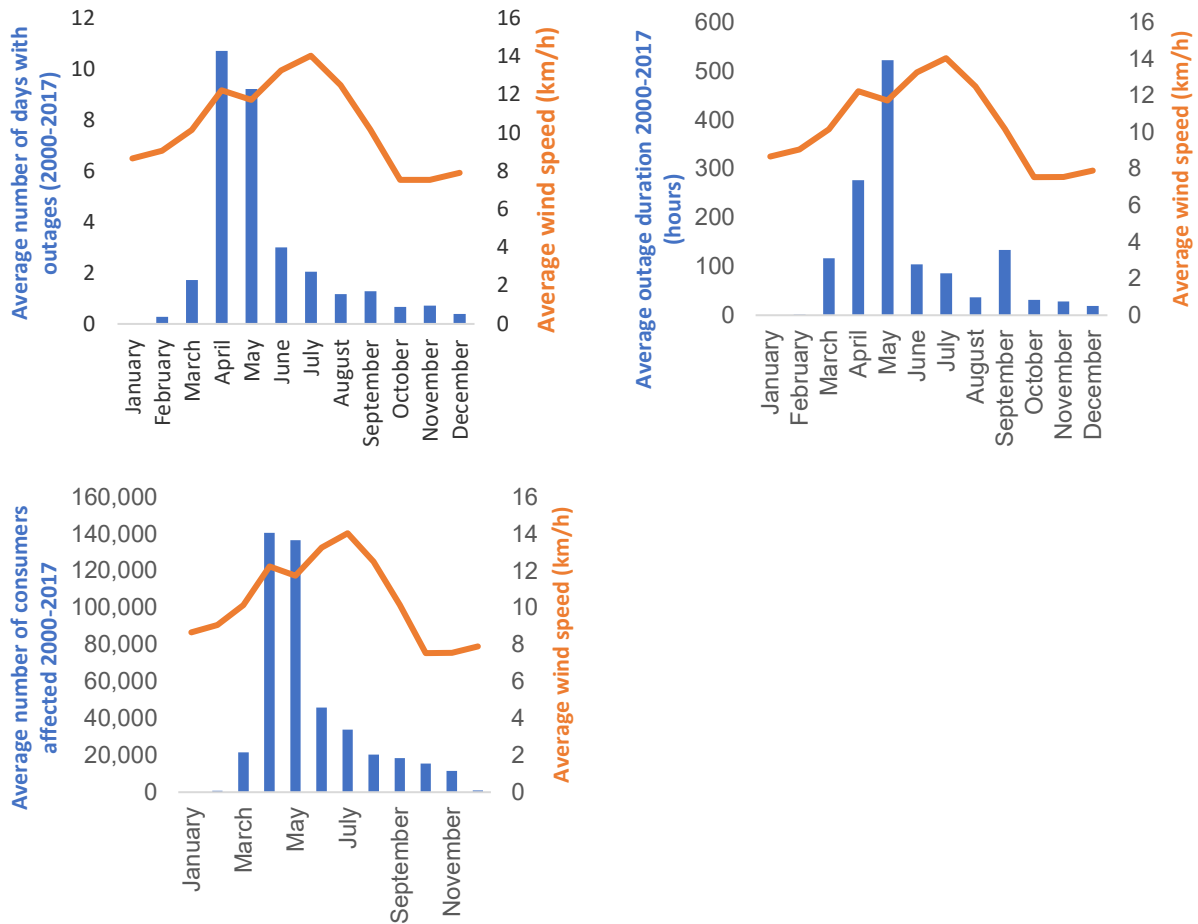
Figure 4.4 demonstrates that outages do not match the monsoon season that is captured by average wind speeds from the ERA5 climate data (see 2.2.2). However, the significant increase in the variance of wind speed from April to May suggests the occurrence of more high intensity storm days caused by severe local convective storms (Nor'wester). As described in section 2.2.2, these storms can be proxied by data on lightning strikes. The seasonal pattern of lightning strikes resembles strongly the occurrence of power outages, thus confirming that most power outages that occur in Bangladesh due to natural causes, are indeed caused by Nor'wester storm in the months April and May. This observation is consistent across the entire data period from 2000 to 2014, as the high correlation between outages and lightning strike time series confirms (Figure 4.6).

Figure 4.5: Outage frequency and lightning strikes
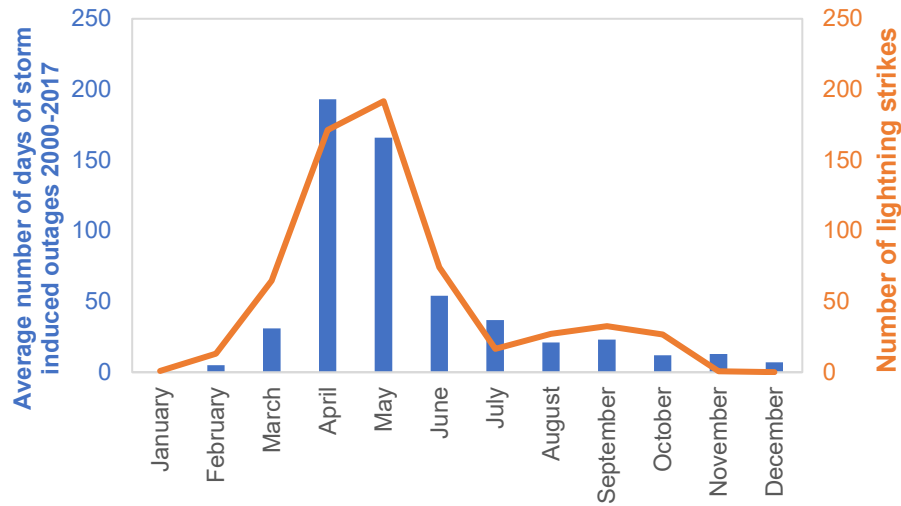
Source: *authors based on BREB electricity performance data and* NASA Tropical Rainfall Measuring Mission Lightning Imaging Sensor (LIS)

Figure 4.6: Time series for outages and lightnings.
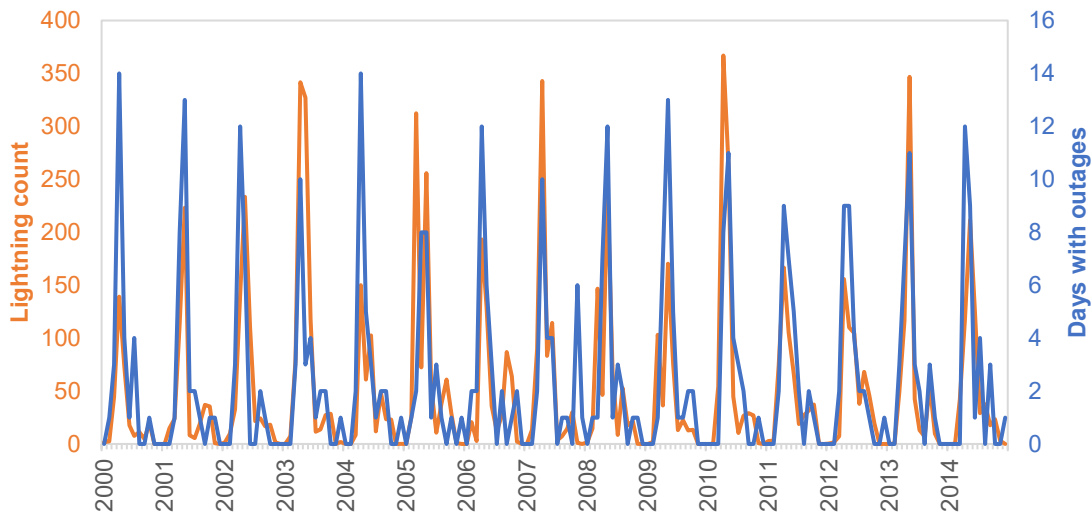
Source: *authors based on BREB electricity performance data and* NASA Tropical Rainfall Measuring Mission Lightning Imaging Sensor (LIS)

To better understand the correlation between power outages (caused by natural shocks) and severe local convective storms, we further disaggregate the lightning data by Dewan et al. (2017) using seasonal maps for the period 1998–2014 (Appendix 5). Seasonal weights were assigned to divisions, depending on the average number of lightnings each of these divisions experienced over the considered period, thus allowing us to disaggregate the LIS lightning data to the division level. Table 4.3 presents these correlations. Overall, lightning strikes are highly correlated with power outages. The correlation is highest in the divisions of Dhaka (75%), Rajshahi (72%), and Chittagong (49%), which together account for 86% of all storm induced outage days.

Table 4.3: Outage-Climate correlation

Division	Correlation Outages/Lightnings	Share of national outage events that occurred in this division
Barisal	-	0
Chittagong	**0.49**	**19.4**
Dhaka	**0.75**	**46.3**
Khulna	0.19	0.9
Rajshahi	**0.72**	**20.5**
Rangpur	0.26	9.8
Sylhet	0.18	3.2
Country	0.39	100

4.3. System vulnerability to storms

This section aims at determining by how much the probability of observing an outage is increased when wind speed increases. Different definitions of storms are derived from the ERA5 wind data. As highlighted in Section 2.2.2, in Bangladesh these climatic events reflect storms associated with the monsoon season and to a lesser extent to Nor'westers.

For a basic definition of "storms" we count the number of days on which wind speed observations exceed a certain threshold in each state. Starting from 15 km/h, we increase the threshold with constant steps of 5 km/h, in order to identify days with stronger storms. The strongest storms we consider correspond to wind above 35km/h. Table 4.4 summarizes the number of storm days according to the respective thresholds in the period 2000 to 2017 in Bangladesh and the US. Each entry of the climate data corresponds to the average daily wind speed recorded at the centroid of one division or state. In Bangladesh, 0.07% of the days between 2000 and 2017 are classified under the strongest storm (wind above 35km/h), while it is 0.4% in the US during the same period.

Table 4.4: Number of storms per country.

|	Wind speeds				
	> 15km/h	>20km/h	>25 km/h	>30km/h	>35km/h
Bangladesh	7,356	2,528	703	166	35
US	77,250	30,119	11,433	4,329	1,407

Source: authors based on ERA5 data.

We then match the dates on which these storms occurred to the dates on which storm-induced power outages were reported by the energy agencies. This allows us to compute the share of storms that caused power outages in Bangladesh and the US.

Figure 4.7 displays results for both the US and Bangladesh. In Bangladesh, outage reports were issued on 2.5% of the days during which wind speeds were higher than 20km/h and almost on 15% of the days with wind speed above 35 km/h.

In the US too, higher wind speeds are associated with more storm-related outages. However, applying the same storm thresholds as in Bangladesh, the energy system in the US can be seen to experience far fewer outages – thus suggesting higher resilience of the energy system to storms. In other words, a storm day on which the average wind speed exceeds 35km/h is 12 times more likely to cause a power outage in Bangladesh than in the US. This difference in resilience levels is likely to be determined by a range of factors, such as investments in resilient infrastructure, risk-informed planning, and maintenance.

Figure 4.7: Vulnerability of the power network to storms
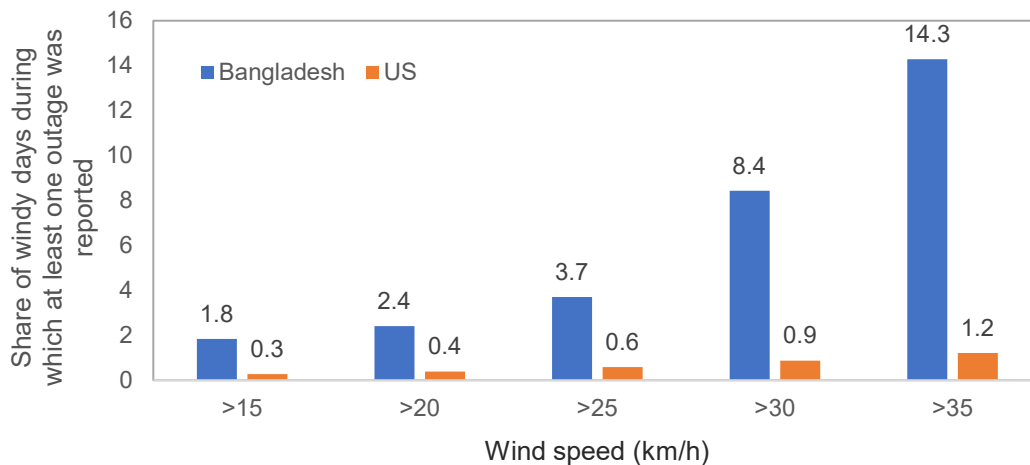
Source: authors Note: The bars represent the share of storm days during which at least one outage was reported.

5. Conclusion

This study has shown that natural shocks – storms in particular – are a significant and often leading cause for power supply disruptions. Even in high-income industrialized economies electricity infrastructure can be heavily affected by natural shocks. The evidence presented in this paper shows that natural hazards are indeed the most frequent cause of electricity supply disruptions in the US – and the second most important cause in Europe. In fact, outages due to natural shocks are not frequent, but also significantly longer than those due to non-natural shocks in – e.g. more than twice as long in the US, and 4.5 times as long in Europe. In terms of outage duration, natural hazards are the most important disruptor in both the US and Europe.

In contrast, in Bangladesh natural shocks account for a far smaller share of power outages – not because energy systems are more resilient, but because system failures and non-natural factors are so frequent that energy users experience daily outages. In other words, a fragile system is vulnerable not only to natural shocks, but also to a host of other stressors and shocks that include unmet demand, equipment failure, and accidents.

Nevertheless, no simple generalizations can be made about the relationship between a country's income level and the vulnerability of its electricity system to natural shocks. In fact, a wide range of factors determine the share of outages that are caused by natural shocks – several of which are analyzed in this study. For instance, hazard intensity and exposure are crucial. In the US, states in the South-east experience a high rate of outages due to natural shocks, as they lie in the path of Atlantic tropical storms. However, even within the US, storms of the same intensity can cause different levels of disruptions in different locations. The study shows that the rate of forest cover, i.e. vegetation, can explain why storms cause more damage in certain places. As trees and branches damage power lines, storms are more likely to be disruptive in forested regions. This also emphasizes the role of maintenance – in regions with high forest cover, maintenance (in the form of tree pruning) is all the more important.

Still, the quality and resilience of the power system itself is key to prevent frequent outages and thus ensure reliable service quality for end-users. As the evidence in this study shows, there are significant differences in network fragility across regions and countries. Using high-frequency climate data, this study shows that power systems in the US and Bangladesh have very different abilities to withstand storms. While the baseline level of outages is already significantly high in Bangladesh, the analysis also shows that the same storm intensity is far more likely to cause outages in Bangladesh than in the US. For instance, wind speeds above 35 km/h are found to be 12 times more likely to cause an outage in Bangladesh than in the US. Overall, these findings suggest that higher network resilience against natural shocks is also likely to result in a reduction of baseline fragility of the network, and thus higher service quality for users. Moreover, we find robust empirical evidence of adaptation effects. This implies that at given levels of baseline fragility, grid operators can exploit experience to design measures specifically effective against natural hazards.

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Appendix

Appendix 1: Adaptation to storm hazards in the US
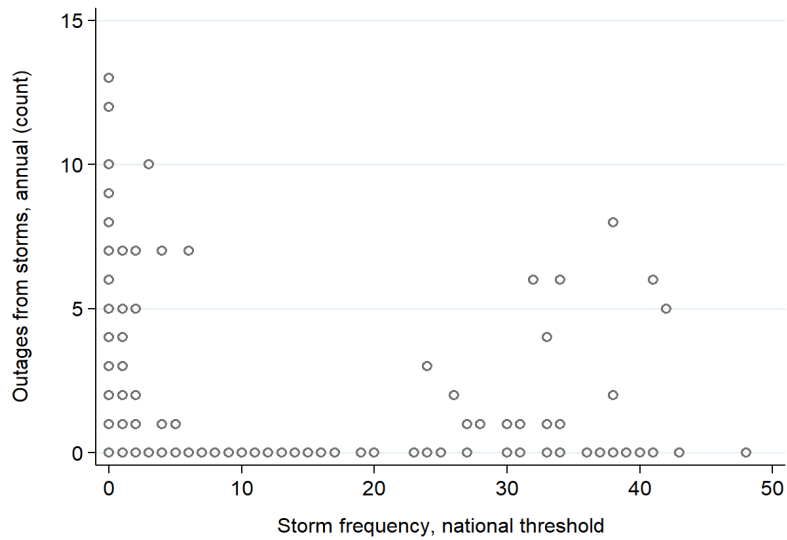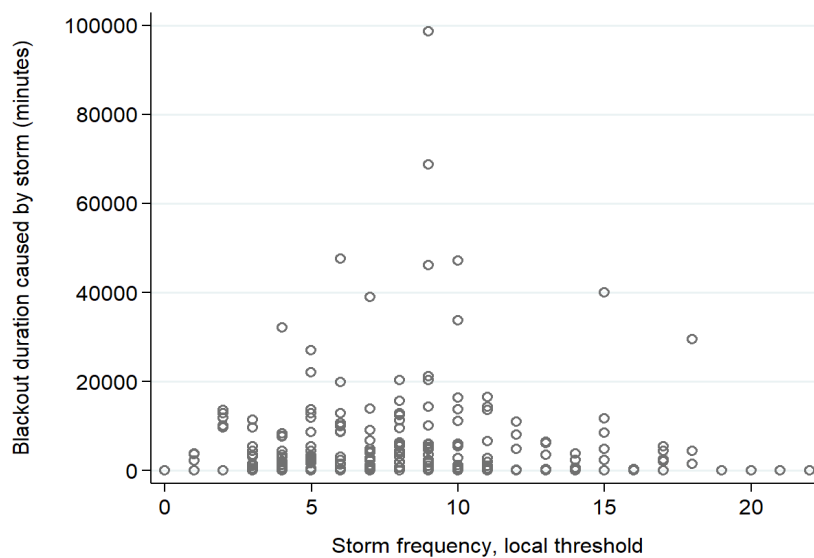

Source: authors

■ *As with outage duration, blackout counts do not seem to be (unconditionally) positively related to storm hazard.*

Appendix 2: Exceptionally strong winds by local standards seem to push blackouts up in the US

Source: authors

■ Defining storms with respect to each state's track records, a positive relation appears to be more plausible.

Appendix 3: Linking storm hazard and the annual number blackouts in the US

Storm blackouts, annual	(I)		(II)		(III)		(IV)	
Storm frequency	0.012		0.011		-0.023	*	-0.007	
(national threshold)	(0.014)		(0.015)		(0.012)		(0.012)	
Grid density			0.0013		0.0021	*	0.0008	
(accounts per km²)			(0.0012)		(0.0012)		(0.0010)	
Fragility			-0.016	*	-0.006		-0.021	
(other blackouts per mil accounts)			(0.009)		(0.010)		(0.024)	
Forest coverage			0.88	***	0.62	*	0.87	***
(% of state area)			(0.33)		(0.33)		(0.17)	
Storm frequency x					-0.0049	**	-0.0026	
Grid density					(0.0019)		(0.0021)	
Storm frequency x					-0.0003	***	-0.0001	***
Fragility					(0.0000)		(0.0000)	
Storm frequency x					0.156	***	0.090	***
Forest coverage					(0.022)		(0.026)	
Power accounts (mil)							0.056	
							(0.037)	
Power generation							0.0035	*
(annual, in GWh)							(0.0018)	
GDP per capita							-0.11	
(relative to US average)							(0.29)	
Year FE							YES	
Constant	0.58	***	0.25		0.33	*	-0.67	**
	(0.08)		(0.16)		(0.18)		(0.33)	
N (state-years)	911		882		882		833	
R-squared	0.00		0.02		0.04		0.41	

Pooled OLS, standard errors clustered on state level in parenthesis. Significance levels: *** 0.001, ** 0.01, * 0.05.
Source: authors

∎ Very much confirms the findings documented with Table 1.

Appendix 4: Linking storm frequency and blackouts WITHIN states, across time

Storm blackout density	(I)		(II)		(III)		(IV)	
Storm frequency	0.0089		0.0084		-0.0042		-0.0207	**
(state-specific threshold)	(0.0086)		(0.0086)		(0.0098)		(0.0100)	
Grid density			0.0033	**	0.0017		-0.0013	
(accounts per km^2)			(0.0015)		(0.0016)		(0.0016)	
Fragility			0.0027		-0.0382		-0.0965	**
(other blackouts per mio accounts)			(0.0160)		(0.0409)		(0.0402)	
Storm frequency x					0.00016	***	0.00018	***
Grid density					(0.00004)		(0.00004)	
Storm frequency x					0.0039		0.0083	*
Fragility					(0.0046)		(0.0044)	
Power accounts							-0.0008	**
(in 1000)							(0.0004)	
Power generation							-0.0016	
(annual, in GWh)							(0.0052)	
GDP per capita							-0.019	
(relative to US average)							(0.564)	
Year FE							YES	
Constant	0.227	***	0.011		0.140		2.447	**
	(0.070)		(0.122)		(0.127)		(1.108)	
N (state-years)	900		900		900		850	
R-squared	0.00		0.01		0.03		0.22	

Dependent defined as annual number of storm blackouts per mio power accounts. Estimated with panel OLS (within estimator). Standard errors clustered on state level in parenthesis. Significance levels: *** 0.001, ** 0.01, * 0.05.

- What matters is the **interaction of storms and grid density**.

- Robust to various controls.

- Including forests is infeasible, since it is invariant at state level.

Appendix 5: Studied Bangladeshi districts and corresponding divisions

Division (Adm1)	District (Adm2)	Division (Adm1)	District (Adm2)
Chittagong	Brahamanbaria	Dhaka	Netrakona
Chittagong	Chandpur	Dhaka	Sherpur
Chittagong	Chittagong	Khulna	Jessore
Chittagong	Comilla	Khulna	Jhenaidah
Chittagong	Cox's bazar	Rajshahi	Joypurhat
Dhaka	Gopalganj	Rajshahi	Naogaon
Dhaka	Jamalpur	Rajshahi	Natore
Dhaka	Kishoreganj	Rajshahi	Pabna
Dhaka	Munshiganj	Rajshahi	Sirajganj
Dhaka	Mymensingh	Rangpur	Gaibandha
Dhaka	Narayanganj	Rangpur	Rangpur
Dhaka	Narsingdi	Sylhet	Sunamganj

Source: authors based on BREB data

Appendix 6: Spatial and seasonal distribution of lightnings in Bangladesh
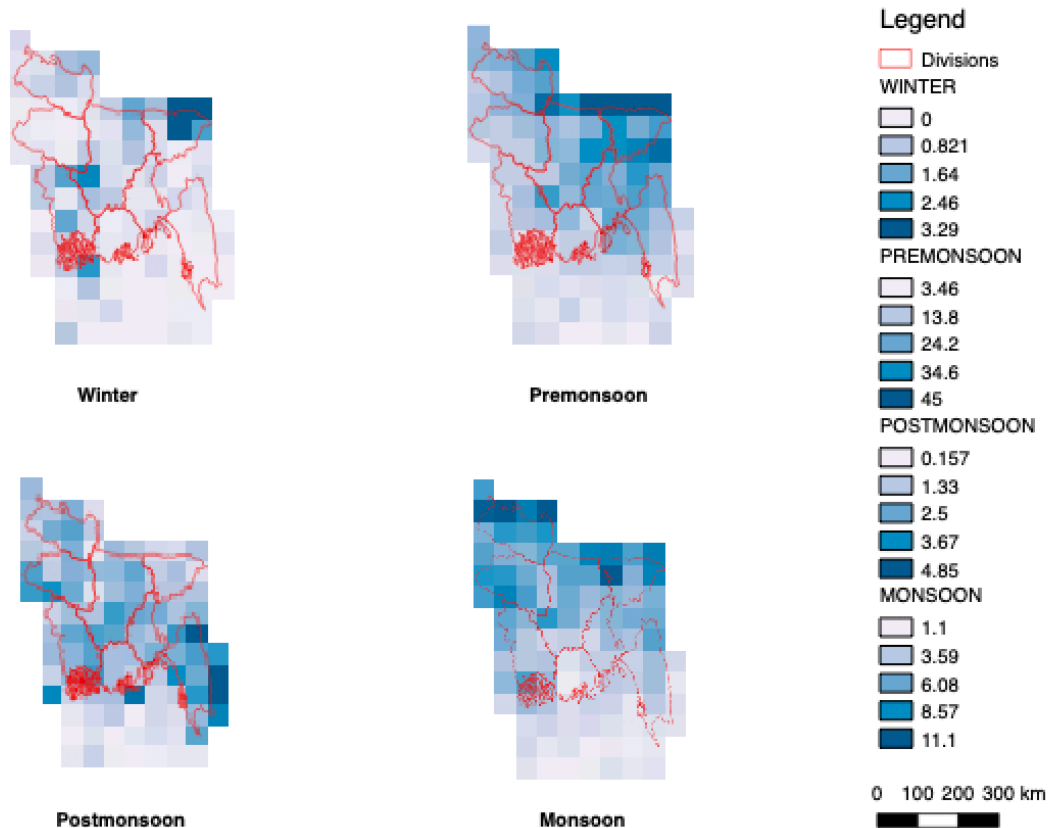
Source: (Dewan *et al.*, 2017)

Appendix 7: Linking wind speeds with storm-related power outages in Bangladesh.

	Model I	Model II	Model III
Average wind speed (km/h)	.0737861*	.0741472*	.0001373
	.0364233	.0370071	.0307878
Year FE		Yes	Yes
Month FE			Yes
Constant	-.3958653	-.4310814	-.0395375
	.3788927	.4024564	.2701147
N	1512	1512	1512
R²	.0402017	.0459067	.2479745

Dependent defined as monthly number of storm blackouts per division. Estimated with panel OLS (within estimator). Standard errors clustered on state level in parenthesis. Significance levels: *** 0.001, ** 0.01, * 0.05.

- The wind data, that captures the events related to the monsoon season, does not have a strong impact on the number of reported outages.

Appendix 8: Linking lightnings with storm-related power outages in Bangladesh.

	Model I	Model II	Model III
Lightning	.0049246	.0050056	.0017224
	.0029484	.003013	.0023859
Year FE		Yes	Yes
Month FE			Yes
Constant	.0878332	.1480673	.015012
	.152212	.1270205	.1465426
N	1260	1260	1260
R²	.1742253	.1780963	.234818

Dependent variable defined as monthly number of storm blackouts per division. Estimated with panel OLS. Standard errors are clustered on division level. Significance levels: *** 0.01, ** 0.05, * 0.10.