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The use of remote sensing technology in power system planning and operation in developing countries.

A synthesis of EEG funded research

A review of the use of satellite technology, sensors, and smart meters in power systems in Ethiopia, Ghana, India, Pakistan and the Kyrgyz Republic.

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Abstract

Satellite data, remote sensors on power systems and smart meters are three examples of remote sensing technology that are becoming more commonly used in developed economies for the planning and operation of power infrastructure. Such technologies have potential applications in developing countries as well, however. This paper briefly reviews the existing literature on the use of such technologies in practice. It then goes on to use the findings from five research projects funded by the Applied Research Programme on Energy and Economic Growth in Ethiopia, Ghana, India, Pakistan and the Kyrgyz republic to explore four questions:

1. What novel approaches in the use of satellite data may be relevant to planning or monitoring of electricity systems?
2. How can sensors be affordably and usefully deployed to help utilities monitor electricity distribution systems?
3. Where smart meters have been introduced, what has been the impact of 'smart' features such as post-paid automated billing, on-line bill payment, remote disconnection and reconnection capabilities, and 'real time' information provision on utility performance?
4. What are the common challenges, if any, of introducing the above digital technologies in the context of power systems in emerging economies?

The paper demonstrates compelling reasons to continue to explore the use of remote sensing technologies in power system planning and operation in developing countries. However, it also cautions that capabilities and costs may be barriers to their adoption by national planners in some cases, while in other situations local political issues may mean their full functionality is not exploited, raising the danger that the costs of deployment exceed potential net economic benefits.

Acknowledgements

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Introduction

Satellite data, remote sensors on power systems and smart meters are three examples of remote sensing technology that are becoming more commonly used in developed economies for the planning and operation of power infrastructure. Much of this technology has potential for applications in the power sectors of low- and middle-income countries as well. This paper briefly explores the literature on deployment of satellite derived data, power network sensors and smart meters in emerging economies and then, in that context, considers the findings of five research projects executed under the auspices of the Applied Research Programme on Energy and Economic Growth (EEG).

The EEG programme ran from 2016-2022 and was funded by the UK Foreign, Commonwealth & Development Office (FCDO). EEG focused on ground-breaking research on sector reforms, innovative technologies and practicable solutions to some of the most pressing energy-related challenges in Sub-Saharan Africa and South Asia. Priority research areas included energy access, renewable energy, power system reliability and the efficiency and productivity of energy uses.

Context

The use of various forms of remote sensing to assist in the planning or operation of electricity systems in middle- or low-income countries has been the subject of research in recent years. Three particular areas of interest have been the use of satellite data, the use of remote sensors on grid transmission and distribution lines, and the introduction of smart meters for domestic and industrial consumers.

Satellite data

Satellite data has been used for some time as a source of data for renewable energy resource planning. Satellite-derived measurements of surface solar irradiance are used to develop high-resolution spatial solar resource assessments (Martins, 2020), with examples of general application in developing countries including West Africa (Neher, Crewell, Meilinger, Pfeifroth, & Trentmann, 2020) and Borneo, Indonesia (Ruiz, Sunarso, Lbrahim-Bathis, Murti, & Budiarto, 2020) or more specifically to explore the potential for rooftop solar in Vietnam (Vu, Nguyen, Huong, Hanh, & Doan, 2020). Likewise, satellite platforms for synthetic aperture radar (SAR) or scatterometers have been used to assess wind resources in, for instance, Morocco (Mabchour, El Had, Zourarah, & Mordane, 2021) and China (Wei, Duan, Liu, Jun, & Sun, 2019). Satellite mapping has been used in hydropower planning in developing countries, for example to identify potential hydropower generation sites in India (Dudhania, Sinhab, & Inamdara, 2006) or to assess the vulnerability of existing hydro infrastructure to climate change in Malawi (Falchetta, Kasamba, & Parkinson, 2020). Satellite data has also been used in conjunction with least-cost electrification modelling to find the most economic mix of grid, mini-grid, and stand-alone technologies to provide universal access to electricity, for example in Nigeria (Blechinger, Cader, & Bertheau, 2019) or to simply map the extent of existing electricity access (Correa, Shah, & Taneja, 2021; Arderne, Rogate, & Antone, 2019; GoamX, Wu, Gao, Niu, & Chen, 2022; Ru, Li, & Belay, 2022). Finally, a collaboration between the Rockefeller Foundation and four universities is currently attempting to develop a facility using satellite imagery to support electricity consumption forecasting across Africa, to help utilities and system planners improve the planning and provision of electricity in the continent (Smart Energy International, 2020). Such research is in addition to use of satellite data for monitoring and planning by national and international energy companies.

Sensors on grids

As costs reduce and functionality increases, the use of remotely deployed sensors on power distribution systems is becoming common in developed economies, to measure quality and reliability of services. Sensors have the potential to provide utilities with better visibility of their distribution systems, meaning they can shift from reacting to news from their customers about power disruptions on their systems to being able to use a higher level of monitoring and control to manage distribution assets and to dispatch crews to deal with faults as soon as they occur (Power Grid International, 2021). Sensors can help utilities track outages and analyse historic data to support decisions about asset management and future investments needed to minimize those areas that are prone to outage (Landis+Gyr, nd). Connected to switches they can also help distribution systems to 'self heal' by isolating faults and automatically re-routing power to as many customers as possible while the fault is dealt with (Larson, 2022). Sensors can also be used to measure the temperature of grid wires to determine whether they are getting too hot (too much electricity flowing through them) or where there is still capacity on the network (Kleiner, 2022). Such use of sensors can be combined with computing at the source of data collection, in the same device that generates the data or as close to it as possible ('grid edge computing'). This can help optimise energy use and cost, while ensuring energy availability and power quality (Iberdrola, nd).

In Sub Saharan Africa and South Asia, attempts to rapidly expand access to electricity are leading to capacity-constrained grids that can lead to poor quality electricity services that include voltage fluctuations and blackouts (Jacome, et al., 2019). Unreliable electricity across Africa hinders entrepreneurship and job creation, is thought to reduce the probability of employment, has an impact on education, and, by increasing the labour intensity of domestic chores, can also inhibit the participation of women and youth in the workforce (Trace S. , 2020). Meanwhile, voltage fluctuations can affect or damage commercial and industrial appliances and healthcare equipment (ibid). To remedy this, governments and global development organizations are prioritizing investments to improve electricity reliability in low- and middle-income countries (Klugman N. , et al., 2021). However, while utilities in high-income countries have augmented grids with increasingly advanced sensors, as discussed above, the deployment of such digital instrumentation in low- and middle-income countries has been limited to date (Nwaiwu, 2021). Where grid-monitoring equipment exists, it typically monitors only at the transmission tier of the grid, providing limited insight into performance issues like outages and voltage sags at the distribution tier. Without measurement at the distribution tier, utilities struggle to get actual insights that would help to improve reliability.

Smart meters

The financial cost to utilities worldwide from non-technical losses is reported to be as much $96 billion each year, with nearly a quarter of those losses, $23.2 billion, occurring in India, and with 17 other countries experiencing losses of over $1 billion per year (Bellero, 2017). In emerging markets, non-technical losses are a major issue for utilities and can be as high as 40% of the total electricity distributed (Glauner, Glaser, & et-al, 2018). Digitalisation, in the form of smart meters, is often put forward as a technical solution to the problem of non-technical losses (see, for example: (Boateng & Ghansah, 2015)). Advanced Metering Infrastructure (AMI) smart meters can offer two-way communication, allowing utilities to remotely disconnect non-paying consumers without the intervention of revenue collection staff, avoiding possible problems of fraudulent collusion between them and customers. Smart meters can also support remote automated billing, reducing costs by removing meter readers, improving accuracy of metering, and again avoiding opportunities for fraudulent collusion with consumers (EEG, 2016).

AMI meters are increasingly being deployed across Africa (Nhede, 2020), South Asia (Shrestha, 2020; Shoukat, 2022; Jones, 2021) and Central Asia (see below). There are not many studies reported in the literature that look at the impacts of smart meter deployment in emerging economies either on consumption or utility revenue recovery. Some references that purport to do this, focus on the introduction of pre-payment functions rather than broader smart features; for example in Ghana (Otchere-Appial, Takahashi, Yeboah, & Yoshida, 2021), and in Uzbekistan (ADB, 2021). A paper summarising the experience of implementing smart meter trials in South Africa (SAMSET, 2015) touches on impacts of improvements to operational efficiency and more accurate billing. The most referenced and rigorous study in the literature is on Kyrgyzstan, looking at the impact of the introduction of smart meters on the quality of electricity supply (Meeks, Omuraliev, Isaev, & Wang, 2021).

Research questions emerging from the literature and relevant EEG research projects contributing findings to this paper

Based on the brief review of literature above, a number of research questions arise in the context of in lower- and middle-income countries:

1. What novel approaches in the use of satellite data might be relevant to the planning or monitoring of electricity systems?
2. How can sensors be affordably and usefully deployed to help utilities monitor distribution systems?
3. Where smart meters have been introduced, what has the impact of 'smart' features such as post-paid automated billing, on-line bill payment, remote disconnection and reconnection capabilities, and 'real time' information provision on utility performance? What challenges have been encountered?
4. What are the common challenges, if any, of introducing the above digital technologies in the context of power systems in emerging economies?

The remainder of this paper seeks to use the findings of five pieces of research sponsored by EEG between 2017 and 2022 to provide some insights and discussion around each of the above four research questions. The projects are summarised in the table below.

Research location / lead researcher(s) / Institution	Research description
Ethiopia **Peters, J.** **Rheinisch-Westfälisches Institut für Wirtschaftsforschung (RWI)**	Electricity demand forecasting in agriculture. How can machine learning techniques and satellite data best be combined with classical on-the-ground surveys to yield informative demand forecasts regarding productive uses in agriculture that ultimately also inform electricity system expansion?
India **Burlig, F.** **University of Chicago**	Tracking India's COVID-19 impacts and recovery using high-frequency electricity and pollution data. A solution to the challenge of tracking economic activity at a high temporal frequency and high spatial resolution. Using satellite data to analyse reflect the overall damage to the Indian economy during the coronavirus lockdowns, but also provide insight into the variation in impact across different regions.
India **Sudarshan, A.** **University of Chicago**	Smart metering and electricity access: the effect of smart metering on revenue collection, electricity access and supply. Evaluation of the ability of smart metering with prepayment to break the cycle of low payment leading to restricted and low-quality supply in India. It aims to answer whether smart metering can improve cost recovery, and thereby energy reliability and access.
Ghana, Kenya **Wolfram, C** **University of California, Berkley**	GridWatch - Measuring electricity reliability with GridWatch sensors. The development, testing, deployment, and operation of a suite of low-cost, remote sensing devices, collectively called GridWatch to measure power outages, voltage fluctuations, and frequency instabilities, initially in Accra, Ghana and subsequently in Kenya.
Kyrgyzstan & Pakistan **Meeks, R.** **Duke University**	The role of metering and infrastructure improvements in power system resilience during COVID-19. A study analysing the impact of COVID-19 on electricity distribution companies and exploring how the pandemic has affected the efficacy and resilience of metering systems and infrastructure upgrades in reducing loss and/or increasing cost recovery.

Innovative approaches to the use of satellite data

The following two research projects both took a novel approach to the use of satellite data with respect to electricity systems, by using satellite capabilities to remotely measure the presence of pollutants in the atmosphere.

Detecting emissions from diesel-powered irrigation to guide planning for extension of the grid for productive use in Ethiopia (Lukuyu J. , et al., 2022)

With 58 million people continuing to live without electricity, Ethiopia has the third largest energy access deficit in the world, after Nigeria and the Democratic Republic of Congo (World Bank, 2021). In response, the Government of Ethiopia's National Electrification Plan (NEP 2.0) aims to reach 100% electricity access by 2025, with 65% of the population accessed through the grid and the rest through off-grid solutions (IEA; IRENA; UNSD; World Bank; WHO, 2021). Despite efforts to implement this plan, with hydroelectric resources being developed at a high pace, research suggests that rural households, which comprise 80 per cent of Ethiopia's population, will have very low consumption patterns for quite some time (Peter, Taneja, & Bensch, 2022).

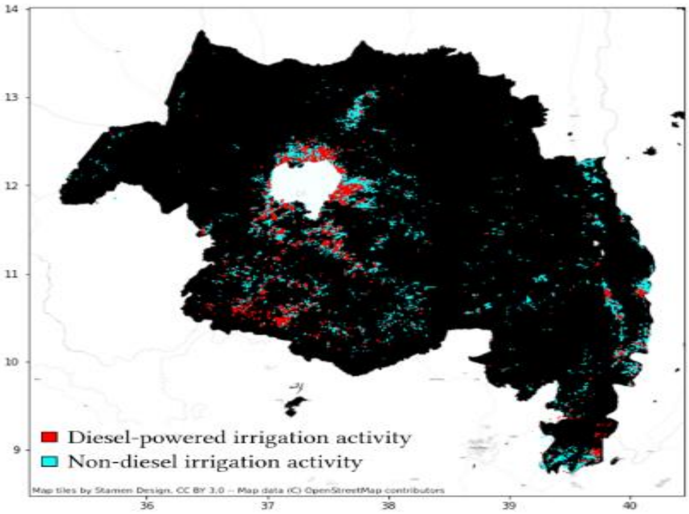
Currently, about 2% of agricultural land in Ethiopia is irrigated, with smallholder farmers largely relying on diesel-powered or manually operated pumps for irrigation. An estimated 200,000 diesel-powered irrigation pumps were in use nationally in 2019 (GIZ, 2020). Reliance on these fuels is unsustainable, as well as detrimental to human health and the environment, with the combustion of diesel releasing pollutants such as nitrogen oxides, carbon monoxide and particulate matter into the atmosphere (Fiebig, Wiartalla, Holderbaum, & Kiesow, 2014). Switching from diesel-powered to electric pumps, therefore, has the potential to increase the developmental impact of electrification while providing an anchor load to ensure financial viability of any grid extension. To this end, Ethiopia's NEP 2.0 prioritizes extension of grid access to areas with the highest potential for irrigation and agricultural processing, considering the particular importance of agriculture for rural livelihoods and noting the opportunity for diesel pump substitution (Federal Democratic Republic of Ethiopia, 2019, pp. 92-93).

This study sought to identify communities with significant potential to shift from diesel powered to electric powered irrigation. In consultation with the Ministry of Agriculture, it took place in six districts in the Amhara and six districts in the Oromia regions. The study utilised a novel approach that combined the use of satellite-measured pollution, crop cover, elevation and surface water data, with machine learning, to identify fossil fuel-powered irrigation activity in Ethiopia. Satellite data was collected for 6,178 plots. Supervised machine learning classification techniques were used to take advantage of the relationship between irrigation seasons and seasonal variation in pollution and crop cover data sets. The machine learning algorithm was 'trained' using a comprehensive data set collected through on-the-ground agricultural surveys. This 'ground truthing' involved household interviews of a random sample of around 1,250 farmers to get information on socio-economic status, crop cultivation and irrigation practices.

The satellite data consisted of daily readings of NO_2 and CO pollutants that were sourced from the Tropospheric Monitoring Instrument on the European Space Agency's Sentinel-5 Precursor satellite for the period January 2018 to July 2021, at a spatial resolution of 7x3.5km^2 (which changed to 3.5x5.6km^2 from the 6th August 2019). In addition, remotely sensed vegetation cover data was sourced from the Moderate Resolution Imaging Spectroradiomonitor (NODIS) on NASA's Terra satellite for every 16 days, at 250-metre resolution for the same period and areas as the pollution data. Elevation, water availability and settlement patterns were also all considered as variables that influence methods of irrigation.

Comparison with the agricultural survey 'ground truthing' data showed that the methodology was able to correctly predict the locations of diesel-powered irrigation pumps in 75% of cases, meaning it has potential to inform planning approaches. Information on where diesel-powered irrigation already exists is important, as it represents sites more likely to have stable revenue from electricity sales in rural areas where, beyond irrigation, little other potential economic activity may exist. For actual grid extension planning, thus derived information will need to be complemented with data on population size, levels of existing access to electricity, distance to grid, industrial or other potential productive loads and so on

Figure 1: Predictions of diesel-powered irrigation activity in the Amhara region of Ethiopia. (Lukuyu, et al., 2022)



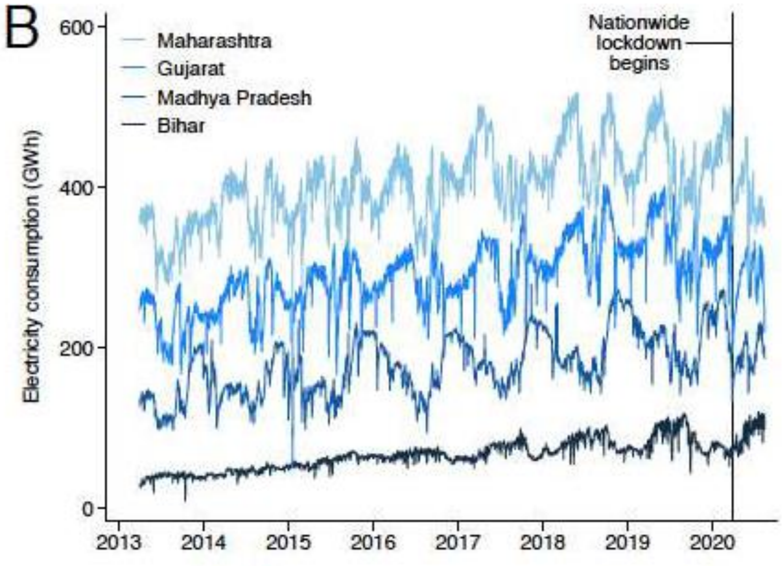
Though the study showed promising results, the limited ground-truth sample size collected, and the nature of the publicly available satellite data meant the researchers concluded it would be difficult to generalise findings beyond the study regions. The researchers argued that using higher resolution satellite imagery could overcome some of the challenges encountered in the initial study. They explored the option of using data from the Planet remote sensing system which could provide data on vegetation at a 3m resolution as opposed to the 250m resolution of the MODIS satellite used in the original exercise. The study proposed to extend the work by using satellite imagery with a higher spatio-temporal resolution combined with deep learning techniques to perform the same task of identifying areas with existing diesel-powered irrigation. This would mean data on vegetation could be extracted at the farm plot level (as opposed to multiple plots at present), providing more tailed patterns of information for model training (Lukuyu, Taneja, & Bensch, 2022). A downside of the shift from MODIS to Planet data sets would be that the former is a publicly available free resource, while the latter is relatively expensive to source.

Tracking India's COVID-19 impacts and recovery using high-frequency electricity and pollution data (Burlig & Sudarshan, 2020)

Damage from the COVID-19 pandemic stemmed from both the direct health costs of the virus and the economic costs of corresponding policy responses, including the impacts of decreased economic activity during COVID-19 lockdowns. Between 25th March 2020 and 20th April 2020, India imposed a stringent lockdown that placed severe restrictions on economic activity. The IMF estimated that the Indian economy shrunk by 25% between April and June 2020[1]. For the Government to best respond to such a crisis, it is critical that information is available that helps understand where economic activity is stable, failing or recovering in order to know where to target support. However, most traditional economic indicators such as employment numbers, tax receipts and formal manufacturing sector output are generally unavailable at a high enough frequency to be useful in emerging economies such as India. The data problem is further compounded by the size of the informal sector in the country, meaning official statistics often report only on a part of the entire economy.

This study used electricity and air pollution data, both of which have been closely linked to economic activity and both of which are available on a high frequency basis, as an alternative approach to painting a more nuanced picture of the various impacts of COVID on the Indian economy. State specific daily electricity consumption data was collected from the Government-owned electricity grid operator - Power System Operation Corporation Limited (see figure 2).

Figure 2: Example of daily electricity consumption for selected states (Burlig & Sudarshan, 2020)



[1] As reported online by the Chief Economist of the International Monetary Fund: https://twitter.com/GitaGopinath/status/1301178474351202306.

Although on-the-ground monitoring of NO_2 (a common pollutant associated with the transport sector) does occur in India, the research team found that data was frequently missing and sparse or non-existent in small towns and rural areas in the country. Instead, the researchers used satellite data sets from the Ozone Monitoring Instrument (OMI) for NO_2 and the Moderate Resolution Imaging Spectroradiometer (MODIS) for Aerosol Optical Density (AOD, a proxy for particulate matter pollution). These data sets are provided daily across the globe. Using these data sets, the research team was able to construct daily measures of electricity use and air quality over a five-year period. This then formed a set of baseline data against which deviations from historical electricity use or air pollution could be measured. The size and negative or positive nature of these deviations then could provide indications of the degree to which the economy had been damaged or was recovering. Comparisons of actual figures compared to predictions based on pre-pandemic data are shown for both the lockdown and its immediate aftermath period (25th March to 30th June) and a post-lockdown 'recovery' period (1st – 30th July) for electricity consumption (Figure 3), NO_2 (Figure 4), and AOD (Figure 5).

Figure 3: The percentage difference between actual state-wise electricity consumption figures during lockdown and immediate aftermath (left) and during the recovery period (right), as compared to predicted values for same periods based on pre-pandemic data

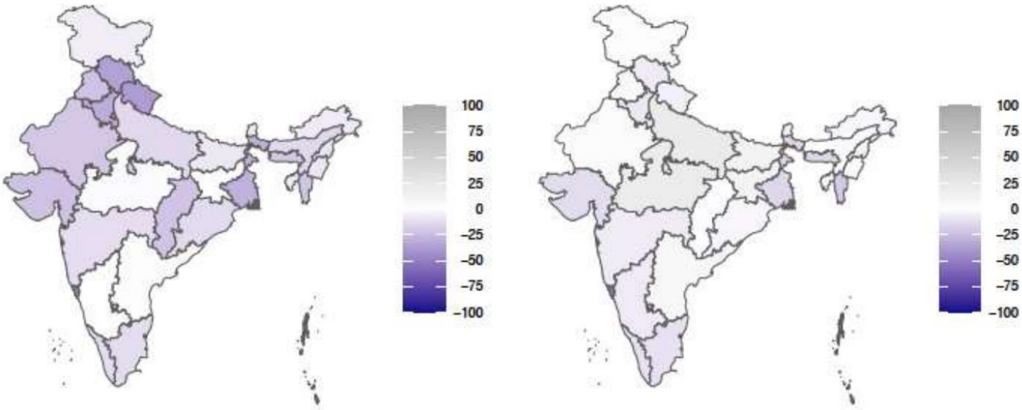


Figure 4: The percentage difference between actual state-wise NO_2 pollution figures during lockdown and immediate aftermath (left) and during the recovery period (right), as compared to predicted values for same periods based on pre-pandemic data

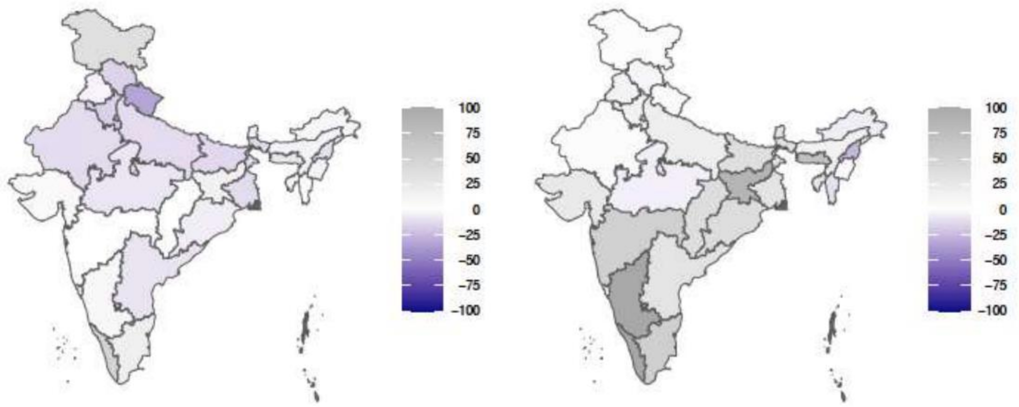
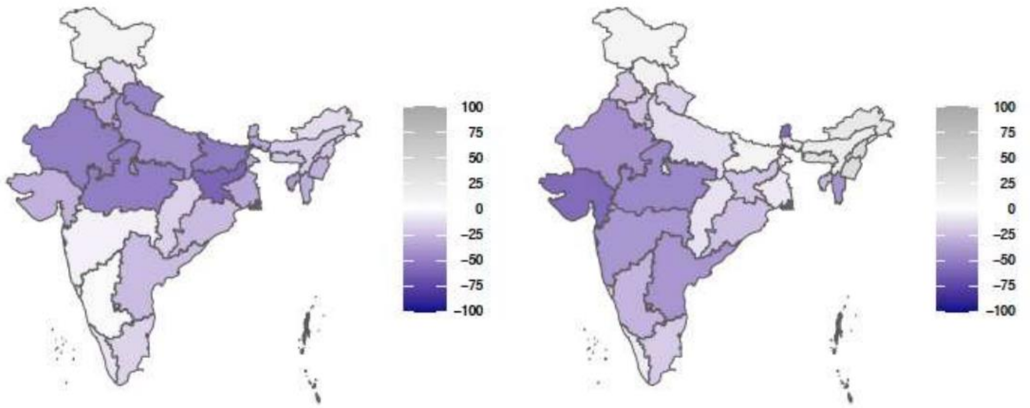


Figure 5: The percentage difference between actual state-wise AOD pollution figures during lockdown and immediate aftermath (left) and during the recovery period (right), as compared to predicted values for same periods based on pre-pandemic data



The results demonstrated that both air pollution and electricity consumption could be used to gain important insights around economic activity following an incident such as the outbreak of the coronavirus pandemic. Across all three measures there was evidence of a widespread economic downturn across the country immediately following the lockdowns, with several areas remaining subdued over a month after the lockdown had eased, with lower than usual electricity consumption especially concentrated in the more industrial states of Gujarat and Maharashtra. NO_2 levels returned to near normal levels more quickly, suggesting that the vehicular activity may have started to recover more quickly. The broader indicator of air quality, AOD, is much more variable than either electricity or NO2 and is therefore much harder to predict. On average, we the study found that air quality in India improved during the COVID-19 lockdowns, with a reduction in AOD of 25.8% relative to baseline levels. It also found evidence of incomplete recovery, with levels still depressed by 17.2% in July. The intensity of the decline varied, with states in India's more polluted northern region such as Madhya Pradesh, Rajasthan, Bihar, and Delhi seeing air quality increase substantially during the lockdown period, but lower improvements elsewhere. Interestingly, while some recovery was visible in July in states such as Bihar, Uttar Pradesh, and Delhi, in states where electricity consumption continued to be below 'normal' for the time of year (e.g. Gujarat and Maharashtra) air quality as measured by AOD continued to improve.

The Use of Sensors on Grids

Measuring Grid Reliability in Ghana and Kenya (Klugman N. , et al., 2021)

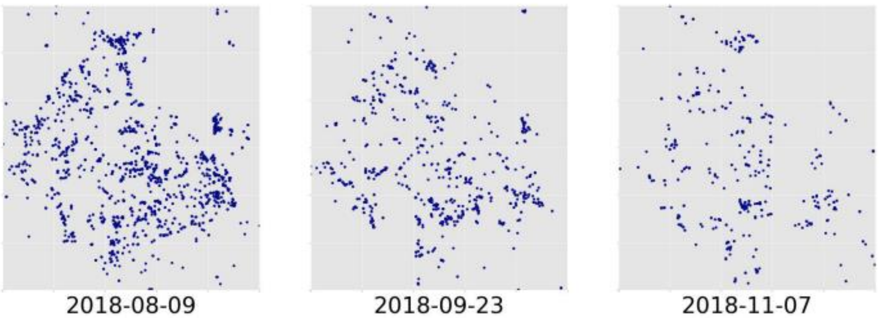
Low electrification rates affect livelihoods and economic growth, so many investment programmes in developing countries understandably aim to deliver new connections. However, as more people gain access to electricity, it is important for policy makers to understand the quality and reliability of that access, with power outages and voltage fluctuations often being widespread and frequent (Wolfram, n.d.). Studies on the macroeconomic impacts of outages suggest the costs may be large – in the range of 2-3% reduction in long-run GDP per capita. In Ghana, for example, the 2013 World Bank Enterprise Surveys found that 61.2% of businesses see electricity reliability as a major constraint (ibid). Unreliability of supply matters for households as well as businesses. For example, a survey of 2180 urban households across major urban centres in Ethiopia found 41% or respondents expressed a willingness to see their monthly electricity bill doubled in return for power outages dropping from a typical eight outages of five hours each per month to one outage of one hour per month (Meles, et al., 2021).

The two commonly used metrics of energy reliability are the System Average Interruption Duration Index (SAIDI) and the System Average Interruption Frequency Index (SAIFI). SAIDI is calculated as the total duration of interruptions in a year divided by the total number of consumers, while SAIFI is calculated as the total number of interruptions in a year divided by the total number of consumers (Hesmondhalgh, Zarakas, & Brown, 2012, p. 23). Currently, the power utility operating in Accra is dependent on customers calling in when a power cut occurs to estimate SAIDI and SAIFI at the low-voltage level, although it does have a system of sensors on feeder lines, substations, and transmission to estimate these ratios for outages that occur at medium and high voltages. Reliance on customer calls for low voltage information has a number of problems: customers will not always call in when they experience an outage, and also may actually not experience outages when they occur (if they are out or asleep when it happens for example). In addition, few customers would call in to say when the power comes back on, making it difficult to use customer calls to measure outage duration to calculate SAIDI (Klugman N. , et al., 2019).

This research involved the deployment of a suite of low-cost, remote sensing devices with the aim of improving the understanding of reliability issues, and the calculation of SAIFI and SAIDI ratios in the low voltage distribution system, initially in Accra, Ghana. The original deployment involved a mix of 362 custom 'PowerWatch' sensors that plug into household sockets and transmit data over the cellular network, and over 3,000 downloads of a mobile app which transmits data on outages when mobiles are connected to the power supply for charging (Klugman N. , et al., 2019). The sampling strategy for the project involved multiple sensors being placed under a single transformer. When all sensors in such a group report an outage at the same time, it indicates that this was due to an issue affecting the transformer rather than a single customer. Likewise, when sensors below multiple different transformers report outages simultaneously, it can be inferred that the outage occurred at a higher level of the grid. The approach has the advantage of being independent and not having to rely on permissions from the utility to instal sensors on their equipment. However, the data from these distributed sensors can be more 'noisy' than data from sensors on utility equipment as householders can potentially remove the static sensors from plug sockets or delete the app from their phone. In an attempt to reduce this 'noise', the project provided householders hosting the static or mobile based sensors with mobile air-time credit in return for them continuing to host the sensors.

There were initial logistical challenges with distributing and managing the network of sensors and it was found that the drop-out rate for users of the mobile phone app was high over time (see Figure 6). As a result, the study focussed on the PowerWatch meters as the main route to data collection.

Figure 6: Relative locations and numbers of active android app events over time (Klugman N. , et al., 2019, p. 7)



Between June 2018 and September 2019, PowerWatch detected 3,123 outages ranging from large outages from high- and medium-voltage faults upstream of the consumer, to small outages stemming from failures in the low-voltage network near the consumer. The full set of outages is shown in Figure 7 below.

Figure 7: All outages PowerWatch detected from June 2018 to September 2019 (Klugman N. , et al., 2021)

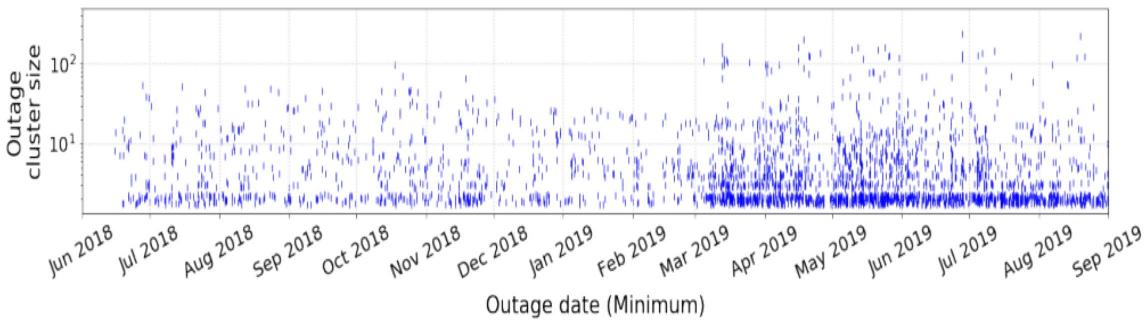


Figure 7 visualises the outages on a timeline where the y axis shows the size of the outage (as the number of sensors impacted) on a log scale. PowerWatch detected 3,123 outages with an average duration of 1.7 hours over the trial period. The longest outage lasted over 48 hours.

A comparison of outage data from PowerWatch sensors and data reported by the Electric Company of Ghana (ECG) was made in the third quarter of 2018. The ECG report included few low-voltage outages because there is no low-voltage automated monitoring. ECG reports are aggregated by district, allowing the project to compare aggregate sensor readings for the same geographical area over the same time period for a direct comparison. The results of the exercise showed that the aggregate readings from the PowerWatch sensors closely matched the SAIFI reported by ECG, but that PowerWatch also detected a substantial number of smaller outages that ECG missed. This data suggests ECG is under-sampling the grid and underreporting smaller outages that affect customers.

The research project demonstrated that endpoint sensing in households and businesses can capture significant grid events that are currently unobserved, assessing the scale and scope of grid performance issues while maintaining utility-independence. The PowerWatch study was able to deploy inexpensive sensors to capture substantially greater number of precisely low-voltage outages than an operating utility could monitor using its existing system, whilst still matching the Utility's' ability to observe high- and medium-voltage outages. This was achieved at a fraction of the cost of the Utility's system, creating a financially viable path toward high- and medium-voltage monitoring for the most resource constrained utilities in the future. The small inexpensive sensor solution which is utility-independent also frees regulators and independent evaluators from reliance on the very utilities they are tasked with auditing.

The deployment of smart meters

Partial use of smart meter capabilities in Haryana State, India (Sudarshan, Burgess, & et_al, 2022)

A large-scale neighbourhood-level randomised control trial in Haryana, India, was undertaken in the towns of Karnal and Gurgaon where a smart meter rollout was being implemented and over 60,000 smart meters had already been installed. At the time of the start of the study, the meters were functioning as traditional electromagnetic meters with 'smart' features such as remote disconnection, real-time data transfer, remote billing, or pre-payment options not yet activated. Individual 'smart' features could be switched on remotely by software functions, providing an experimental environment to compare the impacts of smart and traditional meters. The remote billing experiment was started in March 2021 and ran to September 2021 (at which point all the consumers in the manual billing control group were also moved to remote billing) and involved consumers across 100 binders in four sub-divisions (Abdul Latif Jameel Poverty Action Lab, 2022).

Alongside this, following discussions with the appropriate teams in the utility, a treatment and control list of payment defaulters was prepared to compare the effectiveness of using a protocol for remote disconnections using the smart meter functions against traditional decision making and manual disconnection of consumers with persistent high arrears. These lists were provided over the period July 2021 to April 2022.

Analysis of the results of the automated billing trial looked at three variables – average billing, electricity consumption and revenue collections. The experiment found that all three variables decreased slightly in populations where consumers switched to online billing. Billed amounts fell by about 6% where 80% of the populations were switched to online billing and by 8.5% where there was 100% online billing. Consumption also reduced by similar amounts, while collections fell by 4.8% for the population where 80% were using online billing and 2.9% for those where 100% online billing was implemented, although these estimates were described as "more noisy" (Sudarshan, Burgess, & et_al, 2022, p. 9).

The remote disconnection trial was not successful. In practice, field officials disconnected only 17% of the consumers flagged for disconnection in the lists provided, with no statistical difference in the probability of disconnection in treatment (manual disconnection) and control (remote disconnection). Discussions with the utility led to the researchers being told that it would be impossible to follow a rule-based protocol for disconnections, as disconnection requests arrive from multiple directives and officials and that sub-divisions have to factor in reasons based on demography, political connections, etc. that cannot always be put on paper. In short, utility field officials proved both unwilling to give up discretion in their enforcement choices and unwilling to take consistent action against households with high arrears. The failure to implement the remote disconnection protocol meant the utility effectively chose to forgo its main lever to improve revenue recovery or remove persistent non-payers from the network (and in the process potentially provide a more reliable service for the remaining consumers). This in turn threw into question the validity of the decision to replace old meters with expensive new smart meters in the first place, a move which involved considerable capital expenditure. In this case, the electricity utilities were incurring costs of INR 103 per month per consumer over an eight-year period from the vendors who installed the meters but were only seeing cost reductions as a result of switching from manual meter reading to on-line billing of INR 9.62 per month per consumer. These operational and policy decisions further suggest that, at least in this case, the technology used to meter is not the primary constraint in effective enforcement, and thus utility revenue recovery.

Partial use of smart meter capabilities in the Kyrgyz Republic (Isaev, Meeks, & Omuraliev, 2022)

This research was a follow-up to an earlier study of smart meters in the Kyrgyz Republic (Meeks, Omuraliev, Isaev, & Wang, 2021) which found that the two-way communication provided by the meter allowed the utility to access information on outages and other service quality problems (e.g., voltage fluctuations) within the distribution system, enabling faster and more targeted responses. The original research was based on an experiment focussed on 20 neighbourhoods (1,600 households) in one city. The transformers, and their respective households, were randomly assigned to treatment or control status, with smart meters installed in all 798 houses in the treatment group, while 846 control houses retained their old meters. Electricity prices remained the same across both groups during the study period. Results confirmed that the smart meters led to improvements in service quality, with reduced incidences of voltage fluctuations among the treated group, relative to the control (presumably because of quicker and more targeted responses to problems from the utility).

The follow-on research funded by EEG sought to understand, from the perspective of distribution companies, whether the efficacy of these smart meters in reducing losses and improving quality of supply demonstrated in the earlier study helped with power system resilience during the COVID pandemic. This study targeted the 43 local offices of three of the four distribution companies that provide electricity in the Kyrgyz Republic (Osh Electric, Sever Electric and Vostok Electric). The researchers secured 57 interviews with engineering or finance officers across the 43 offices that covered just under 2 million residential and industrial consumers, of which a fifth of the former and a third of the latter were connected to the grid via smart meters. The study found 63% of respondents feeling that smart meters mitigated the challenges and pressures on the distribution companies as a result of the pandemic. More interestingly, in the context of this synthesis paper, the study also found that, as in the Haryana case, the full functionalities of the smart meters were not always used by the utilities. For example, (unlike Haryana) 79% of the respondents do use their meters' smart features to remotely disconnect and reconnect customers when necessary (e.g., for non-payment of bill or where electricity theft is identified). On the other hand, again in contrast to the Haryana example, just 7% use smart meters' remote billing functionality, with the vast majority of bills still issued manually.

Discussion

The EEG funded research outlined above demonstrated the potential of remote sensing technologies in improving electricity planning and operations. This included the novel use of satellite-derived air pollution data for both identifying potential areas where grid extension could be made more financially viable through productive use (irrigation) and providing high frequency information on economic activity. The research also demonstrated how low-cost sensors on the consumer end of distribution systems could provide additional fine-grained real-time data on outages on low-voltage lines, which could in turn be aggregated to provide real-time information on issues with medium- and high-voltage lines at a fraction of the cost of traditional sensor equipment used by utilities.

While these research projects show potential for application in developing country contexts, several challenges exist. The satellite-based approaches require access to significant computing power and human capabilities to interpret satellite imagery and utilise machine learning techniques, which may not be present within concerned planning authorities or other national institutions. Also, while the research exploiting the diesel emissions from irrigation pumps to identify potential areas for grid extension utilised satellite data that is freely and publicly available, it concluded that higher resolution images would be more effective – a choice that would incur costs that may present a further barrier to the adoption of the approach where it would be most useful. The PowerWatch sensors demonstrated a cost-effective approach to monitoring grid reliability, but their application to date has remained in the hands of the research team and the technology has yet to be taken up by a regulator, utility or other accountability agency or group.

Meanwhile the case studies discussing a remote sensing technology that has made it into mainstream use in developing countries - smart meters - offer different lessons. In both the Haryana and Kyrgyz Republic cases, the full functionality of the technology was not used, with the remote disconnection functionality ignored in the Haryana case and the remote billing option ignored in the Kyrgyz Republic case. In both instances this would have resulted in sub-optimal economic benefits being accrued by the utilities from the introduction of the technology; in the Haryana case to the extent that there would have been a net cost rather than a net benefit from the deployment of smart meters. The Haryana case study furthermore demonstrates how much the unlocking of the 'benefits' of such technology is dependent on the political economy in which it is deployed.

In summary, data derived from remote sensors, machine learning, satellite imagery and smart meters can only be useful if it is being used effectively. There can be many reasons why this is not so in practice. For example, while there is openness and willingness to use satellite data, energy system planners in developing countries might not have the necessary skills and capacity to access and interpret data and use it efficiently. Likewise, investing in the installation of technology such as smart meters can be expensive and needs to be justified in terms of improvements in revenue recovery or reduction of losses. But experience shows that it is not always that case the that all the capabilities and features of a smart meter will be used when installed.

The research summarised in this paper shows how remote sensors, machine learning, satellite imagery and smart meters are improving data collection and addressing data gaps – which should ultimately help to improve electricity access in developing countries through informing energy system planning – but stakeholders must be supported to ensure that data is accessible and can be used effectively. Continuous engagement between research teams, policy makers and utilities is needed to make full use of the insights being generated. This can also help build the human capacity that will ultimately be required to unlock the full potential of remote sensing technology in practice.

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