The Digital Transformation and Disruptive Technologies: Challenges and Solutions for the Electricity Sector in African Markets

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Abstract

The rise of disruptive technologies is profoundly transforming systems of production and management across sectors and industries, but primarily in wealthy countries. This paper considers how disruptive technologies could help improve power sector reform and development in African markets. In particular, it explores the role that might be played by the Internet of Things, cloud computing, and advanced analytics. After reviewing current trends in disruptive technologies, the paper illustrates the application of key elements with use cases in the areas of power infrastructure planning, power sector operations, and off-grid electrification. Finally, the paper looks at context-specific challenges to the widespread implementation of disruptive technologies. While disruptive technologies offer innovative ways of tackling some of the main challenges of traditional approaches to power sector development, their widespread adoption hinges on a concerted effort across public and private players to lend support to key aspects such as improved broadband connectivity, a vibrant startup scene and surrounding technology ecosystem, or simply the right to Internet access.

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1 Introduction

A number of new, "disruptive" technologies are creating a new way to approach global challenges. The concurrent emergence of technologies such as big data, the Internet of Things, cloud computing, and sophisticated analytics has led to a new trend, popularly referred to as *industry 4.0*, characterized by an increasingly seamless interplay between the physical and the digital. This has paved the way for radical transformation of whole sectors and industries across the globe. Perhaps somewhat hidden from the hype surrounding these advancements are the opportunities they present for developing regions, and African markets in particular.

Africa's emerging technology (tech) landscape is characterized by the rapid rise of the number of tech hubs across the continent, which have contributed significantly to Africans putting their own distinct spin on Web 2.0[1] technology as a tool for tackling local socio-economic challenges. From Nigeria to Kenya, Rwanda to Ghana, tech innovation has already begun influencing various sectors, including healthcare (LifeBank, n.d.; BISA, 2017), mobility (Ma3Route, 2017; GidiTraffic, 2015), agriculture (M-Farm, 2017), and education (Eneza Education, 2016; Efiko, n.d.). Kenya's famous Ushahidi—a crowd mapping platform that collects eyewitness reports and geo-locates them on a digital map, providing a visual overview of situations and hotspots—has proven to be a powerful information tool globally, especially for development agencies and political activists (BMZ, 2016). Notwithstanding the buzz in tech industry, current adoption rates and impact of industry 4.0 technology are still very low in most African countries owing to a number of limitations—notably poor infrastructure.

Still, with industry 4.0 enabling an unprecedented level of data gathering and of communication of physical systems both with humans but also with each other in real-time, it presents tremendous opportunities for placing countries onto a much more speedy and sustainable path of development—including, ironically, to help build modern infrastructure. As an example, in the electricity sector some of these breakthrough technologies are increasingly being harnessed to enhance power sector development by improving the quality of power delivery to existing grid users as well as by providing access to the 1.2bn (IEA, 2016) that currently lack it.

Following positive experiences with the adoption of mobile phones and (to a lesser extent) the Internet across the continent, the paper looks at how these new technologies can be used to benefit African economies and societies, just as they do in other regions. And while they will not all be suitable for each African country's local context, the aim of this paper is to highlight the potential of some of the current technological trends, focusing on the electricity sector.

This paper begins by introducing the digital transformation towards the Fourth Industrial Revolution (Section 2) and the underlying technology trends (Section 3); Section 4 then provides a brief overview of the impact disruptive technologies have had on people and businesses; Section 5 explores some innovative applications of disruptive

[1] Web 2.0 refers to the phenomenon of a growing number of platforms and services with a novel combination of existing web technologies; in their service offerings they are characterized by a high degree of participation, networking, and social interaction (Wirtz et al., 2014).

tech in the electricity sector across developing countries; specific use cases of these solutions are presented in Sections 6 (infrastructure planning), 7 (grid operations), and 8 (off-grid generation); key challenges to the uptake of disruptive tech in African countries are discussed in Section 9; Section 10 lays out recommendations for support; and Section 11 concludes.

2 The digital transformation towards industry 4.0 and underlying trends

To understand how we arrived at this point, it is useful to recall the impact of previous industrial revolutions: the first industrial revolution introduced water and steam to mechanize production; the second one introduced electricity to power mass production; and the third made possible automated production through the use of electronics and information technology (Schwab, 2015).

The term 'industry 4.0', originally coined by the German government (GTAI, n.d.), specifically refers to the phenomenon that traditional manufacturing and production methods are in the midst of a digital transformation that goes far beyond simple automation of production. The increased blurring of lines between the physical and the virtual has given birth to so-called cyber-physical systems—networks linking IT with mechanical and electronic components, enabling communication amongst them (Deloitte, 2015).

The *Fourth Industrial Revolution,* builds on the others; it is characterized by a fusion of technologies that is blurring the boundaries between the physical, digital, and even biological spheres. The speed of current breakthroughs is unprecedented, evolving at a non-linear rate, and their impact can be felt across countries and industries as they transform entire systems of production, management and governance.

Industry players in advanced economies are investing significant resources in industry 4.0 because traditional productivity levels have been widely exhausted (McKinsey & Company, 2015). In addition, as time-to-market and customer responsiveness are today's key factors of competitiveness, companies in developed countries are very keen on investing in technologies that can match low labor cost levels, regardless of location.

But cyber-physical systems don't only connect machines with each other. More generally, they create a smart network of machines, properties, ICT systems, smart products, and individuals across the entire value chain and the full product life cycle (Deloitte, 2015). Industry 4.0, therefore, is not the mere implementation of any single technology or even the combination of several. Instead, it can be understood as the efficient and powerful harmonization of emerging disruptive technologies, including the Cloud, the Internet of Things, Analytics and Artificial Intelligence, Robotics, and 3D printing (Ramachandran, 2016). The key for all of these pieces to work together in an orchestrated and effective way is the *constant flow of information*.

3 Underlying trends powering disruptive tech

Disruptive technologies are technologies that displace established ones to shake up existing industries or even create entirely new ones (Christensen, 1997). Technologies that are currently disrupting industries across the spectrum are also often referred to as *exponential technologies*—that is, any technology accelerating on an exponential growth curve (i.e. doubling in power on a regular basis, e.g. computing power) (Diamandis & Kotler, 2015). Notable ones are the Internet of Things (IoT); cloud computing; artificial intelligence and advanced analytics; advanced robotics; and additive manufacturing (McKinsey & Company, 2015; Diamandis & Kotler, 2015).

Cloud computing and the *Internet of Things* (IoT) are the main industry 4.0 concepts discussed in this paper. The IoT itself is not a new concept as the term was coined back in the late 1990s. In fact, many of its key components, including semiconductors and wireless networks, have been in use for decades (UK Government Office for Science, 2014). Instead it is the rate at which it is developing that is remarkable. The IoT is made up of hardware—connected devices—and software components—the networks that link them as well as powerful cloud-based data storage platforms and analytics programs to further process the data (UK Government Office for Science, 2014). Technological advancements, in particular of networks & sensors and computing capacity, discussed in more detail in the following sections, have contributed in significant ways to the recent surge of disruptive tech.

3.1 Networks and sensors—the basis of the IoT

A network refers to any interconnection of signals and information. Examples include the Internet, 4G, Wi-Fi, and Bluetooth (UK Government Office for Science, 2014). A sensor is a device that detects information, such as temperature, vibration, radiation, etc. When connected to a network, a sensor can then transmit that information. Networked sensors are increasingly being embedded in all our 'things'. And it is this explosion of connectivity—estimates predict between 21 and 50 billion interconnected devices by 2020 (Gartner, Inc., 2015; Evans, 2011)—together with the radical drop in cost especially of sensors that has been driving the Internet of Things (IoT) ecosystem (Diamandis & Kotler, 2015; UK Government Office for Science, 2014). Networks and sensors transport enormous amounts of very useful data. These data become valuable even beyond gaining new knowledge once automation is introduced as it enables the direct translation of collected data into a series of subsequent consecutive actions to be executed without human intervention (Diamandis & Kotler, 2015).

Networks and sensors generate enormous amounts of very useful data. These data become valuable even beyond gaining new knowledge once automation is introduced as it enables the direct translation of collected data into a series of subsequent consecutive actions to be executed without human intervention (Diamandis & Kotler, 2015). Automation is the basis of new types of service offering and is crucial for enhanced effectiveness and efficiency as well as augmented productivity, allowing for unprecedented levels of precision and accuracy across activities (McKinsey Global Institute, 2017).

3.2 Infinite computing—the basis of cloud computing

Infinite computing is a decisive trend fuelling the IoT. The term refers to the fact that computing is constantly decreasing in cost, increasingly powerful, and increasingly available (Diamandis & Kotler, 2015). This trend has also given rise to cloud computing, which provides on-demand, online access to rich application functionality and shared computing power that make it possible to create exponentially scalable solutions on a pay-per-use basis. Companies such as Google, Amazon, and Rackspace each own massive computational facilities, the usage of which they provide to the public as a service. As such, *the cloud* is in effect "democratizing our ability to leverage computing on a massive scale" (Diamandis & Kotler, 2015).

4 Impact of disruptive technologies

The current rise of disruptive technologies in developed countries has already affected peoples' sense of privacy, their notions of ownership, their consumption and communication patterns, the way people work and experience leisure, how people meet other people and nurture relationships, even peoples' attitude towards and control over their health (Schwab, 2015).

The technologies that underpin industry 4.0 are also having major impact on businesses. On the supply side, existing industry value chains are being disrupted and completely novel services are being created. The data that connected 'things' constitute the raw material for all manner of new services, which will be more profitable than the products they are based on (Economist, 2015). On the demand side, increased transparency and consumer engagement, mass customization, and new patterns of consumer behavior are made possible by access to mobile phones, networks and data, and are fundamentally changing the way companies design, market, and deliver products and services, characterized by a high degree of personalization.

Disruptive technologies equally present huge potential for major advancement in various sectors in developing countries. However, owing to a number of constraints (discussed in Chapter 5), current adoption rates and impact of disruptive technologies are still low in most developing regions, particularly in Africa. Connectivity, accessibility and digital literacy remain major challenges on the continent, and neither governments nor the industry generally seem particularly eager when it comes to making investments in new knowledge and technologies for further technology development and integration.

Nonetheless, African countries and countries of other developing regions have the distinct advantage over developed markets of not being burdened by infrastructure legacy issues. And, despite the nascent uptake of disruptive technologies, there are some noteworthy efforts underway. The following innovative solutions in the fields of agriculture, healthcare and water are examples.

Sensors in agricultural fields are used to monitor aspects of the environment such as the weather situation, soil conditions, moisture levels, and rates of photosynthesis in real-time to enable farmers achieve optimal crop production (IBM calls this 'precision agriculture'). The solution essentially takes the guesswork out of farming (IBM Research, n.d.; Zenvus , 2016). With the help of predictive analytics, the resulting information, e.g.

on nutrient requirements, prediction of weather patterns, etc., can then be disseminated to farmers, aggregators, as well as localized crop insurance schemes for optimal decision-making. The collected information also contributes to a growing body of historical (local) weather data and otherwise non-existent databases of information for growing conditions (ITU & Cisco, 2016; IBM Research, n.d.), which can be further integrated into credit scoring algorithms to increase predictive accuracy of scores and suitability of insurance product design (Jackson, 2016).

In the field of healthcare, connected thermometers are used to monitor vaccine delivery and storage in real-time, which is particularly useful for application in remote and rural areas. One of the main challenges for healthcare providers being vaccine spoilage, remote sensing products that monitor and record refrigerator temperatures provide an innovative solution to keeping the 'cold chain' operational. Mobile-enabled temperature sensor devices designed for use in rural health facilities developing countries, for instance, upload data to a cloud-based server in near real-time via GPRS or SMS, sending regular messages to designated recipients about current temperatures as well as warnings when these exceed critical thresholds. Advanced analytics then help managers understand problem points and how related challenges can be resolved (ITU & Cisco, 2016; Nexleaf, 2016).

Water and sanitation is another field that has surfaced innovative solutions. In China, water supply has been monitored with IoT sensor devices mounted at key points to collect data on water usage and flow rates. Smart meters in India have been used to remotely monitor quality and quantity of water. A 'smart hand pump' fitted with a basic accelerometer to capture movement of the pump, using the SMS format to transmit data to staff, has been used in Kenya with the aim to resolve issues related to broken water pumps in rural areas. Similarly, sensor technology is used in Rwanda to monitor pump performance and water flow, notifying technicians via SMS and e-mail (for more information on individual projects see ITU & Cisco, 2016).

5 Disruptive technologies for power sector development in developing countries

The electricity sector, too, is poised to benefit from a combination of disruptive technologies. Providing electricity to the 1.2 billion people globally without access presents a major challenge and opportunity. Only 14 percent of the Sub-Sahara African population has access to grid electricity. Reliable and affordable access to electricity services are fundamental to achieving prosperity and emerging disruptive technologies can significantly facilitate efforts to 'ensure access to affordable, reliable, sustainable, and modern energy for all' by 2030 (United Nations, n.d.).

Mobile services, big data, and analytics in particular have the potential to impact the sector in a major way, potentially improving electricity infrastructure planning, grid operations and the economics of off-grid solutions.

5.1 Mobile-enabled services

Increased mobile connectivity across developing countries has led to the development of a range of mobile-enabled services—mobile financial services being among the most prominent (Suri & Jack, 2016). The other major service enabled by mobile networks is machine-to-machine (M2M) technology, which is a subset of the broader concept of the IoT enabling mobile data transmission between two or more machines (GSMA, 2014).

The confluence of ubiquitous mobile networks, the growth of mobile money services and the availability of M2M have paved the way for new opportunities to create smart solutions for improved access to modern energy services in Africa and other developing regions.

The IoT enables pervasive services based on sensing activities. Providers of electricity services via solar home systems or microgrids in East Africa, for example, use the IoT to manage performance of units and connected devices with respect to a number of parameters, allowing them to easily spot and locate problems. The IoT concept also allows for accurate metering of the electricity systems. It allows for collection and analysis of data received in real-time from their various systems, which service providers can use to give instantaneous feedback to customers to enable them reap the full benefits. It enables remote monitoring of power supply and demand, resolving many issues cost-effectively and reducing uncertainty and maintenance costs (Blodgett et al., 2016). To be able to monitor, connect with and provide remote feedback and support in real-time to customers in far-flung parts of a country is ground-breaking and it renders the traditional argument—that providing rural segments of the population with electricity is not financially viable—a less potent one.

With scaling smart meter and microgrid solutions enabled by mobile services, data such as real-time and highly granular information about energy usage and storage levels, functionality of devices, load balancing, and credit data as well as data on payments, refunds, etc., are amplifying the need for big data solutions.

Note that simpler, more cost-effective solutions may prove more effective considering the context of lack of resources. Wireless wide area networks (WWANs) for communication, for example, could provide a lower cost alternative to M2M modules since they use white space spectrum rather than mobile networks with high-speed capabilities (ITU & Cisco, 2016).

5.2 Big data

Crucial to the emergence of the big data concept are digitalization[2], increasing access to and use of the Internet, and the dramatic rise of information generated via networked devices. Definitions of this (often-disliked) term vary widely, but, generally speaking, big data refers to collections of datasets so large, varied and complex that traditional data management and data processing tools and applications are not sufficient to deal with it (McKinsey Global Institute, 2011; Wikipedia, 2017; Oxford English Dictionary, n.d.). In

[2] Gartner defines digitalization as the process of moving to a digital business; i.e. the use of digital technologies to change a business model so as to create new revenue streams and value-producing opportunities (Gartner, 2017).

addition, the generation of new insights from big data often hinges on the ability to integrate large volumes of data from disparate sources.

Satellite or aerial imagery is one major source of big data. It can be particularly useful when combined with seemingly disparate or unrelated location data or with change detection over time. The same image can therefore be used to unearth different information depending on its level of detail (i.e. resolution) and what other data it is joined with. Satellite images of rural parts of a country, for example, paired with factors such as pricing and technical data on equipment for power production, various demographics, and the proximity of buildings enables calculation of load estimates and provides key figures to entrepreneurs for potential microgrid designs, perhaps even detail of necessary equipment (Spatocco, 2015). These types of solutions potentially make microgrid development, and more generally development of other distributed generation technologies, more likely to be financially viable and allow the microgrid business a greater chance to scale.

Another source of big data that has recently proven relevant to the electricity infrastructure planning of a region are mobile phone records. The winner of Orange's *D4D Senegal* challenge established that call record data (CRD) could provide an accurate proxy of detailed spatio-temporal distribution of energy needs. The types of dataset included in the study give an idea of the sheer volume of the data involved: the number of mobile phone subscribers of a particular network provider; the hourly voice and text traffic between each pair of mobile phone towers, including total call duration, number of calls and total number of text messages), etc. (Martinez-Cesana et al., 2015). Note that the data used in this study only covered the period of one year and analysis of changes over time would hold a multiple of the size requirement.

5.3 Analytics: taking big data to big insights

All this big data, however, is of little use without being able to provide 'big insight'. This is where advanced analytics comes into play. Machine learning techniques are applied to large volumes of data to discover patterns and relationships, as a result unearthing previously 'hidden' information. Not only that—as the term implies, algorithms are designed to 'learn' associations they establish between the data points, enabling them to 'predict' future outcomes with reasonably high accuracy.

Going back to the example of satellite images—a machine learning algorithm fed with highly detailed satellite imagery of villages can learn properties of a house, e.g. by size and shape, which it recognizes with increasing precision as the volume of historical data supplied increases (Spatocco, 2015). This allows parts of the work required to identify rural development sites not only be automated but also to be done remotely.

Predictive analytics are also used to target specific customer segments more effectively. A massive body of various electricity usage and transaction data gathered during pilot projects, for instance, allows for highly accurate inferences e.g. in terms of consumption patterns in a particular settlement or region (Powerhive, 2015; Blodgett et al., 2016). Various analytics methods can generate detailed insights. Clustering algorithms, for example, group data together based on certain characteristics such that instances in the same group are more similar to each other than to those in other groups. These insights are then used to design tailored offerings for the various user segments and their needs.

The relative ease of data collection and knowledge extrapolation facilitated by these disruptive technologies is very appealing in the context of developing countries, especially for rural areas or fast-growing urban clusters where historical data of this type are essentially non-existent.

6 Use cases of disruptive technologies for power sector development across Africa

6.1 Enhancing electricity infrastructure planning

The lack of quality data is a major obstacle to infrastructure planning across the developing world. Detailed demographic data as well as comprehensive data on existing infrastructure—at a relatively high level of spatial granularity—are vital for adequate energy infrastructure planning of a country. They are especially important in developing countries where new electricity infrastructure is a crucial element of socio-economic development. Yet, it is this sort of detailed information that is typically lacking in these countries, posing a main challenge to effective planning.

Energy planners often spend a considerable amount of effort acquiring reasonably accurate estimates of electrification costs for a particular area or region. This necessitates knowing, for example, which electrification option is most suitable (e.g. grid vs. off-grid), which in turn relies on reasonably detailed data on demand patterns of consumption units in as well as accurate geo-spatial data of the area under consideration (e.g. distance from existing grid infrastructure, distribution of individual consumption units, etc.). An adequate estimate of costs, i.e. a 'bill of materials', needed for a particular electrification project, requires detailed assessments incorporating the physical location of each structure to be electrified (Parshall et al., 2009). The expense of obtaining this level of detail can be prohibitively high, especially in developing countries.

Particularly for off-grid solutions, the lack of information has as a consequence rendered the planning phase a mostly prohibitively cumbersome and often arbitrary one. Deploying microgrids in rural settings typically consists of developing a solution for a general rural context, then rather subjectively choosing a community—for practical reasons commonly based on connections or location—surveying the location, and finally deploying the solution (Spatocco, 2015). Because very little to no data exists about these rural settings, siting, planning, and scaling decisions are made with little to no hard data and instead rely on anecdotal evidence. This is in fact a common reason for failure of so many rural electrification initiatives as it hinders them from scaling to meaningful levels.

Modern ICT-based approaches leveraging open-source software and open data as well as crowdsourcing techniques have already shown to produce high-quality insight so crucial for effective planning activities in resource-constrained developing countries (Bazilian et al., 2012). In addition, a number of disruptive technologies have recently proven to be effective tools not only providing added granularity to the planning process but also reducing waste by effectively eliminating the need for expensive field-time.

6.1.1 Machine Learning for improved electricity planning

Satellite-based mapping activities can be used to extract rich big data sets of topology and demography of interest where there once existed none. An example is *GridForm*—a planning framework that rapidly identifies, digitizes, and models rural development sites such that parts of the work required to design a microgrid are automated. Developed at MIT's Tata Center for Technology and Design, it is designed to rapidly provide insights that are immediately useful to practitioners on the ground, i.e. types of materials required, estimated project cost, optimal project location (O'Neill, 2016).

GridForm involves processing large amounts of remotely sensed satellite images with machine learning and neural network algorithms for rapid and efficient digitization of thousands of regions (villages/roads/farms) that previously might have been known merely by landmarks or paper sketches (Spatocco, 2015). These layers of data can actually be used further at multiple levels beyond optimization of microgrid planning, for instance to simulate local supply-chain logistics or agricultural growth strategy.

Although this framework specifically addresses barriers to entry for potential microgrid entrepreneurs associated with excessively costly on-the-ground research, it can be extrapolated for more general region and country level planning purposes. The goal remains the same: to accelerate the planning phase in order to reduce costs, and to produce highly accurate hardware and cost models of a target area before anyone even steps foot on the potential site.

Note that one challenge with this approach is that satellite coverage of impoverished areas is currently typically spotty. More imagery collected on a more consistent basis is required to generate more accurate outcomes of this and similar mapping exercises. But experts have expressed confidence that these limitations could soon be mitigated thanks to a large number of new high-resolution satellite images to become available over the next year or so (Martin, 2016).

6.1.2 Mobile phone data for electricity infrastructure planning

The effective modeling of electricity demand requires estimating total peak demand for each sub-location under consideration, for which detailed knowledge of the energy needs at relatively high spatial and temporal resolution is crucial. However with scarcity of energy consumption data in developing countries, adequate estimation of demand profiles requires some alternative form of comprehensive knowledge on human activities and their spatio-temporal distribution.

Recently, the increasing availability of mobile phone data has provided new insights into the mobility patterns of people and the distribution of the population in space and time (Martinez-Cesana et al., 2015).[3] In the developing country context mobile network data is typically much more advanced than energy consumption data, making this a very useful solution. Mobile phone data can also provide much more accurate information on spatio-temporal activity centers than, for instance, satellite imagery and, combined with

[3] This approach won the 'Data for Development Senegal' innovation challenge around ICT Big Data for the purpose of societal development, which ran from April 2014 to April 2015 (Orange, 2016).

existing socio-economic, geo-referenced, climate, or survey data[4], can significantly enhance electrification planning activities for both urban and rural areas (Martinez-Cesana et al., 2015).

Additional detailed mobile phone datasets covering several years could provide even better proxies for electricity needs and population migration, especially when combined with corresponding electricity consumption profiles for different areas.[5] More advanced studies could involve dynamic population mapping derived from mobile phone data for the development of so-called 'risk-maps'. These maps would facilitate the assessment of the number of people affected by a potential blackout and could feed into extension and operation plans of existing power grids (Martinez-Cesana et al., 2015).

6.1.3 Mapping existing electricity infrastructure (KEDCO)

Recently privatized Nigerian distribution utility Kano Electricity Distribution Company (KEDCO) covers three Northern Nigerian states, which is home to approximately 23 million people, the majority of which is currently without access to electricity. In collaboration with Columbia University's Quadracci Sustainable Engineering Lab (qSEL) and with funding from the World Bank, KEDCO was able to leverage disruptive technologies to take stock of the assets and geographic extent of its system by mapping nearly 10 million meters of medium voltage power lines and related equipment. (Carbajal, 2015).

The mapping effort used Open Street Maps (OSM) as an open-source, cloud-based, decentralized mapping tool. The on-the-ground mapping activities involved the use of Android devices loaded with the OSMTracker[6]—an open source product deployed by the OSM community and tweaked for the purpose of mapping electricity infrastructure. Newly collected map data was then uploaded to and edited on a cloud-based platform that could be viewed in KEDCO field offices, Kano headquarters, and SEL staff in New York simultaneously. Disruptive technologies here facilitated review, integration, correction, and validation of map data by multiple users in different locations in a collaborative and timely manner. This has obvious benefits in terms of acceleration of identification and resolution of technical problems and validation of data.

At project inception, the available information about KEDCO's grid distribution system merely consisted of rough maps, single-line diagrams, or other resources that were sufficient for many utility operations but lacked geo-spatial detail required for effective power infrastructure planning. The result of this exercise is a highly detailed database of KEDCO's power distribution network, including the system's grid lines and several thousands of pieces of strategic equipment, e.g. transformers, substations, and generation sites. The map not only enables an accurate measure of the system's line

[4] Some of CGD's work on mobile-phone based surveys include (Leo et al., 2015) and (Morello & Leo Benjamin, 2016). See also CGD's forthcoming work on mobile-phone surveys on energy.

[5] One notable limitation of exploiting mobile phone datasets for wider purposes is that private telecommunications companies are generally unwilling to release or share mobile phone data, except for very rare occasions, such as in cases of collaboration with trusted institutions for research purposes.

[6] The OSMTracker is an offline GPS tracker that works by capturing latitude and longitude at regular intervals while traveling along a route, resulting in an ordered set of points representing a set of connected segments (Wiki, 2016; Natali, 2013).

length but also provides the basis for a data-driven approach to important aspects of operation, such as modeling of cost-effective expansion of grid and off-grid electricity throughout KECDO's jurisdiction, planning and maintenance, load flow analysis, and establishing a customer database (Carbajal, 2015).

6.2 Improving operations

While not so much of an issue in developed countries, transmission and distribution (T&D) losses in developing countries present major bottlenecks. Utilities across Sub-Saharan Africa (SSA) perform worst, with losses of over 80 percent in Togo and an average of 18 percent across the continent. The loss rate in SSA (excl. South Africa) is more than double the world average and that of many developing countries in Asia (OECD/IAEA, 2014). Such high losses make for much less reliable power supply, which is already insufficient in most developing countries.

While non-technical losses (unbilled, uncollected, or stolen) in the power sector are negligibly small in developed countries, they make up the bulk of losses in developing countries. As of 2015, Nigerian distribution companies, for instance, lost 37 percent of electricity delivered to them to collection issues alone (Office of the Vice President of Nigeria/Power Africa, 2015). This is why metering and billing electricity consumed by users is so important. Successful commercial management of an electricity utility, together with effectively collecting the billed amounts, is a critical function of the company's financial health and in generally more effective power supply (World Bank, 2009).

Disruptive technologies have made a big impact on electricity grids across developed countries in recent years with the development of the smart grid. In essence, the smart grid is a power generation, transmission and distribution network enriched by digital control, monitoring and telecommunication capabilities. It enables real-time, automated and two-way flow of both information and electricity, giving all parties along the electricity chain insight into electricity flow and supporting infrastructure. This additional layer of computing intelligence distributed across the existing infrastructure connects assets in what can be called the 'Internet of Watts'—one example of the IoT (Donitzky et al., 2014).

While most developing countries still have major infrastructural, regulatory and financial constraints to overcome for a more comprehensive implementation of the smart grid concept, individual smart grid technologies can help address key issues such as technical and non-technical losses in transmission and distribution networks (Bazilian et al., 2011).

6.2.1 Smart metering to curb electricity losses

In 2012, Ugandan national utility UMEME installed GSM-enabled meters to fight electricity theft. This initiative followed the government's mandated target to improve revenue collection rates from 75 percent to 99 percent by 2018. An additional incentive was to reduce the utility's 40 percent losses (ITU & Cisco, 2016; Metering and Smart Energy International, 2014).

To tackle the challenge of technical losses, UMEME installed smart meters at network nodes (at the level of power line feeders) to determine the branches responsible for the greatest losses, e.g. due to poor network or poor supply. To address non-technical losses, UMEME retrofitted 8,600 households with pre-paid split meters fitted with a keypad that takes a voucher code received upon payment to unlock equivalent electricity supply. Overall, in addition to identifying the most inefficient branches of the network, the utility was able to single out 900 non-billed customers (ITU & Cisco, 2016; Metering and Smart Energy International, 2014).

As a result of the pilot, US$1.5 million (of the US$2.3. million total cost) was recovered over the course of one year alone. An additional US$387,000 was collected in arrears from penalties imposed for late payment. And although the average power consumption per customer decreased by 30 percent as a result of customers having more visibility of their usage, overall revenues increased because tampering with meters and undetected illegal connections became more difficult (ITU & Cisco, 2016).

Encouraged by the results of the pilot, UMEME went on to invest US$24 million in an Advanced Metering Infrastructure (AMI) system enabling two-way communication between customers and the utility provider's server, which it is currently using with large power users—a customer group significantly contributing to non-technical losses (Metering and Smart Energy International, 2014; Mubiru, 2015).

Similar initiatives are underway in several African countries, including Ethiopia (Power Africa & USEA, 2016), Kenya (Metering and Smart Energy International, 2016), Nigeria (Huawai, 2016) and South Africa, where revenue collection was increased by 10 percent in some municipalities when smart meters were installed as un-metered locations and locations with defective meters were discovered (Power Africa & USEA, 2016).

6.3 Connecting the unconnected

Since the launch of Sustainable Energy for All in 2012 and announcement of the goal of universal electrification by 2030, the energy access challenge has attracted significant international and national attention. In order to meet the universal electrification objectives, alternative approaches to grid extension are being pursued, especially in areas with dispersed populations or an inadequate local market. It is estimated that off-grid options will deliver electricity to 60 percent of the non-electrified rural areas (International Energy Agency and the World Bank, 2014).

Microgrid systems in particular may offer one potential solution to meet basic needs while also facilitating modest productive use of electricity. But microgrid deployment faces major challenges. Amongst other things, micro-grid developers have to deal with limited access to low-cost finance, inadequate local skills and capacities (Bhattacharyya & Palit, 2016), and a risky business environment due to unknown consumer characteristics and unfamiliar business activities.

Over the last few years, a number of microgrid solution providers have come up with innovative ways of leveraging disruptive technologies to improve the planning stage and aspects of operations to enable owners scale solutions. Providers like Kenya-based SteamaCo (headquartered in Manchester, UK) and Powerhive (headquartered in

Berkeley, US) leverage the power of mobile and use a combination of IoT, analytics, and cloud-based solutions to electrify rural, off-grid communities in Kenya. Their solutions provide operators with control of site performance and revenue streams through remote, detailed insights into consumption patterns, and the opportunity to rapidly acquire customers and select optimal sites (Powerhive, 2015; Blodgett et al., 2016). Business risks are reduced as more data on consumer behavior is gathered and analyzed. This build-up of historical data in turn increases access to finance, if they present evidence of financial viability. These are all key variables for overcoming traditional challenges of planning for micro grids as well as keeping them running reliably and profitably so as to be able to scale.

What makes these types of solutions all the more potentially powerful is that they provide new insight into consumer characteristics of the area of operation. Data generated via remote monitoring technology on both power generation and power use can be used as a basis for improved product and service design and innovation, thereby contributing toward efforts to scale and effectively tap into the latent rural power market.

6.3.1 Making microgrids a viable option?

From the perspective of grid owners and operators, the microgrid solution involves installing hardware at the power stations enabling them to remotely monitor technical and financial information flows of grids in real-time via cloud-based software. The fact that data flows in real-time means problems, e.g. dips in battery voltage, can be addressed before they become serious, and customers' power consumption can constantly be checked against their remaining balance (Earley, 2015; Blodgett et al., 2016; Blodgett et al., 2016). This means electricity can be connected or disconnected based on customers' real-time account status. It also allows operators to identify spare capacity that could be directed to other, more effective uses.

From the point of view of the customers, this sort of solution means they have flexible access to electricity as credit can be topped up and balances checked in real-time, similar to pay-as-you-go mobile phones. Paying per unit of electricity used allows people to buy electricity according to their earning patterns and domestic needs—a much more suitable solution for some low-income segments of the population. This mechanism is particularly appealing to groups with irregular or seasonal income, as is often the case, for example, with farmers. Also, payment data collected on a largely financially excluded segment of the population can further serve as a basis for financial inclusion of unbanked people as it enables the previously impossible assessment of their creditworthiness.

These solutions, together with data gathered during operation, signal to investors a clear mechanism to manage grid operations and capture payments transparently. Moreover, while the solutions are presented here specifically for microgrids, the same technology can be applied to privatized grid extension—which is, in fact, SteamaCo's plan (Leaf, 2015).

7 Discussion of challenges impeding wider adoption of disruptive tech across Africa

The main challenges appear to be related to the infrastructure and human capital, with some significant regulatory issues requiring attention.

7.1 Technological challenges

One major hindrance for the uptake of cloud-based solutions that enable processing of large volumes of data is the state of cloud computing in developing countries. The scope for cloud computing is much smaller in developing countries than in developed ones. Apart from a lack of awareness, cloud adoption is typically constrained by the high cost of broadband services and limited access to electricity.

Despite notable improvements in broadband connectivity in many developing countries in recent times, the gap of availability of cloud-related infrastructure between developed and developing countries keeps widening. In most low-income countries, mobile broadband networks are characterized by low speed and high latency, which makes them suboptimal for more advanced cloud service provision (UNCTAD, 2013). Note, however, that there are variations in the extent to which connectivity issues pose a challenge across developing countries—least developed countries, for instance, are more affected than countries such as Kenya or Nigeria with multiple providers.

International broadband connectivity in developing countries is often characterized by high costs and unreliable service, and inadequate local infrastructure even further undermines the cost advantage of global cloud provision in these regions. Therefore reducing the physical distance between cloud computing centers and end users would reduce the cost of broadband communication as well as latency (UNCTAD, 2013). However, while constructing local data centers might seem more advantageous considering the cost of accessing centers located far away from the continent, the enormous electricity demands may render this approach unrealistic in many countries. Ironically, power infrastructure is a critical bottleneck to cloud adoption for power service solutions in the majority of African countries.

Since cloud computing goes hand in hand with the IoT, many of the challenges users of the IoT face overlap with those discussed in relation to cloud computing. Power requirements are a main issue, with high bandwidth devices having much higher power requirements (ITU & Cisco, 2016). Connectivity challenges, such as limited data network coverage, are equally relevant to the use of the IoT.

These infrastructural weaknesses present a challenge to the robustness of some of the solutions discussed, requiring workarounds that fit the context. The field data collection for the power infrastructure mapping effort in Nigeria by KEDCO and qSEL, for example, was largely done offline, specifically to avert any problems resulting from quality issues of mobile broadband networks. The offline GPS tracker allowed the mapping team to collect and store data on mobile phones with mini-SD cards in a reliable manner. The process only started relying on broadband networks once the data had been transferred to a PC Laptop via a wired connection and validation/editing was completed. While data operations (simultaneous uploading and downloading by multiple uers) in the cloud still proved to be a challenge due poor network quality, a substantial part of the process like editing and validating data had been completed in the absence of broadband connectivity (qSEL, personal communication, Feb 17, 2017).

Robustness of solutions is obviously of particular concern in end-user facing situations. Ensuring reliable service provision is key to avoid losing customers' trust in the service provision. SteamaCo's solution, for instance, consists of multiple connectivity levels, which makes it particularly relevant to environments constrained by the quality of mobile broadband networks as well as power supply. The two key layers are the cloud and the 'fog'—a networking layer built on the LoRA (Long Range Radio) protocol through which smart meters communicate with each other. This local intelligence enables a certain degree of automation, even in the absence of broadband connectivity. The solution therefore only needs one point of communication with the cloud, and can fall back to communicate via SMS, making it ideal for supply-constrained systems (E. Moder, personal communication, Jan 16, 2017).

7.2 Shortage of relevant skills

The shortage of talent for the digital transformation towards industry 4.0 is a global problem, which is even worse in some developing countries. The shortage of IT-related skills is a significant concern, particularly in African countries, where IT education is poorly developed and where, due to a lack of appealing opportunities locally, those with good IT skills typically leave for much more attractive careers elsewhere.

IT skills are all the more critical where countries and businesses are seeking to establish new business opportunities through the use of disruptive tech, such as examples discussed in the previous chapter. The lack of adequate training infrastructure and skilled personnel poses a significant barrier to the successful adoption of industry 4.0 solutions.

A successful implementation of disruptive tech requires different and/or upgraded IT skill sets and an improvement of the existing skill blend. In many cases it is not even so much the lack of skills as their misalignment that is the problem (Deloitte, 2016). For instance, a lot more software, programming, statistical, and machine learning skills as well as specific skills for data processing are needed to successfully leverage disruptive technologies. Also, the right combination of skills, e.g. IT skills, business acumen but also story telling capabilities for analytics come together in a complementary way in most industry 4.0 solutions. This creates an extensive need for training and/or re-training of the existing workforce to foster understanding and operation of new and smart technologies in a more holistic manner.

Nonetheless, the last couple of years have seen a steady rise in young skilled local entrepreneurs, as well as an influx of diaspora returnees, both fundamentally changing Africa's tech landscape. Many successful tech start-ups invest in on-the-job training of individuals—one way of gradually building a digitally skilled workforce in the absence of a strong education system. Quality work experiences can play a crucial part in filling skill gaps. One example of a successful initiative is Nigerian Hotel.ng's remote (paid) internship program for software developers that consists of sourcing talented and determined coders and using a training-by-doing approach, eventually hiring the brightest amongst them (Essien, 2016).

A few private higher education institutions also play their part in addressing the tech skills gap. Founded by a former Microsoft employee, Ghana's Ashesi University, for example, places emphasis on programming skills across its spectrum of students ('100 percent of students learn to code') and offers a Computer Science program designed to empower young people to harness the power of technology by preparing them to engage with new technologies and create software tools tailored to local needs (Ashesi, n.d.).

Also in Ghana, the Meltwater Entrepreneurial School of Technology (MEST) together with the MEST Incubator program help tackle the skills problem by providing fully sponsored training, investment, and mentoring to aspiring tech entrepreneurs (MEST, n.d.). Andela, a startup based in Nigeria and Kenya, is providing talented young people from all over the continent with high level computer-science instruction. Andela then matches them with companies in the US, Europe, and Africa, using a novel business model to develop and link Africa's largely untapped brainpower with companies desperate for skilled programmers (Lehoczky, 2016).

A key aspect to tackling the ICT skills problem in Africa are tech or innovation hubs that have increased from just a handful in 2010 to several hundreds today (Bright, 2016; Dahir, 2016). From Kenya's iHub (iHub, 2017) to Nigeria's CcHub (Co-Creation Hub, 2012), these hubs have shaped Africa's ICT landscape in major ways. Acting as 'nexus points for technologists, investors and tech companies' (we_magazine, 2011), they have, in fact, become the main backbone of Africa's emerging technology ecosystem.

These spaces have been described as "catalysts for ecosystems developing around technology" and "structural pillars in Africa's fragile IT landscape" (Tayo Akinyemi in Bright, 2016). As such they contribute significantly not only to plugging the fundamental infrastructural gaps that tend to impede digital entrepreneurship, connectivity, technology development, and innovation, but also, and especially, to filling the (digital) skill gaps in response to the continent's demand for IT training (Bright, 2016; Mulligan, 2015). Since these hubs tend to be located in urban centers, however, their overall impact is arguably still limited and would benefit significantly from financial and other support.

7.3 Legal and regulatory issues

Legal and regulatory issues refer to more generally applicable challenges around the implementation of data-driven and cloud-based solutions. These include data localization regulations and resulting limits on cross border traffic of data; interoperability of devices, i.e. their ability to connect with other systems and networks seamlessly and securely; cyber security, portability of mobile services, life cycle policy of devices, communication resources such as Internet Protocol addresses, or questions of ownership of data generated also need to be addressed (Saint & Garba, 2016; ITU & Cisco, 2016).

Cloud-based services, such as those offered by smart utilities, increasingly depend on users' ability to make secure electronic transactions, which requires legislation and financial regulation to give them equal status to physical payments (UNCTAD, 2013).

However, many African countries still lack adequate legal and regulatory frameworks to support e-commerce.

Also, since IoT applications crucially depend on the Internet, it is essential to counter the threat of Internet blackouts as a result of government pressure on local telecommunication companies to shut down access. In 2016 alone, there were at least 11 documented cases of mainly politically motivated shutdowns recorded across the continent (Paradigm Initiative Nigeria, 2016). In line with the UNHRC's declaration in June 2016 affirming that Internet rights and Internet access are human rights (United Nations General Assembly, 2016), the active engagement of governments with the development, implementation, and protection of legal frameworks that protect Internet freedom could facilitate the adoption of disruptive technologies.

8 Possible avenues to address challenges

In general, development partners can contribute to the uptake of disruptive technologies and a digital transformation towards industry 4.0 in African countries by contributing to the financing of IoT and cloud-related infrastructure. This should include the promotion of local data centers, if necessary, and be supported by reliable and quality electricity, strong mobile broadband networks and appropriate tax incentives (ITU & Cisco, 2016; UNCTAD, 2013; Saint & Garba, 2016).

The following is a proposed agenda for support:

1. **Support regulatory reform**

   Supporting the establishment of appropriate legal and regulatory frameworks is crucial for successful implementation of the modern solutions, as discussed above. This requires the creation of master plans addressing the IoT and cloud computing specifically (ITU & Cisco, 2016). In this regard, it is important to note that African countries will require IoT applications that meet the specific needs of the individual country, which will ideally be reflected in adequate enabling policy.

   The IoT applications that are a priority in an African country will be different from those in a Western country. Smart homes, home automation or autonomous vehicles, for instance, are unlikely to be common themes due to low income, poor infrastructure and seen as they provide little value to daily life considering the local context (Saint & Garba, 2016). Instead, the focus is more likely to be on commercial applications such as smart metering solutions or precision agriculture, which are more likely to have a significant and wide-ranging socioeconomic impact across populations and industry.

   The international community can also assist in addressing legal and regulatory issues around secure electronic transactions as well as politically-motivated Internet shutdowns (see Section 9.3)—both of which could help ease the adoption of disruptive tech across the continent.

2. **Support the ecosystem for disruptive tech**

   There are plenty of opportunities for industry, government and international organizations to become involved in the training and development of Africa's digital workforce. This includes training and capacity building efforts and the promotion of policies that facilitate innovation and circulation of skilled labor. Beyond the support of research and innovation by academia, the promotion of a broad and vibrant ecosystem for disruptive technologies, especially through support of tech spaces and innovation hubs across the continent (discussed in Section 9.2), is fundamental.

3. **Promote direct investment in ICT**

   Generally speaking, financing and development of ICT projects, especially IoT- and cloud-based projects, will require collaboration between the private and the public sector as well as development organizations. Note, for instance, that many of the universal service levy amounts African countries currently receive are relatively high—in some cases up to 3 percent of total revenue (GSMA, 2014). However, the majority of these funds often go under- or even un-utilized, lying idle in banks, or being used for other purposes. Such funds could be directed towards the financing of essential IoT technology development (Saint & Garba, 2016).

   Since many solutions based on disruptive tech are relatively new and therefore not yet widely known, they face additional hurdles to securing financing. For smart off-grid solutions such as microgrids or stand-alone home systems, for instance, financial institutions typically want to see a scalable model before committing their funds, while providers require just that financing to be able to demonstrate a scalable model. One solution to this chicken-and-egg problem could be the introduction of bridging mechanisms such as results-based financing, where the developer of a solution pays for set up but is guaranteed payment, such as feed-in-tariffs in the case of an electricity provider, once the solution is up and running (Savedoff, 2016).

4. **Encourage expansion on internet access and implementation of 4G or higher**

   Although the number of 4G-LTE mobile networks in Africa has increased by 34 new networks since the beginning of 2015, extending 4G services to 14 more countries—4G adoption on the continent still significantly lags that of the rest of the world. The main reasons for this include the prevalence of high-frequency capacity spectrum bands typically confined to densely populated urban areas; and the fact that 4G is often operated by niche players only, predominantly targeting business communities and restricting their coverage to major cities (Rizzato, 2016). Countries that have not yet adopted 4G could consider jumping directly to 5G technology to facilitate the expansion of the IoT. Initiatives similar to the proposed US Digital GAP legislation, ideally with special emphasis on the implementation of high-speed mobile networks, are valuable first steps (Kenny, 2016).

9 Conclusion and next steps

While the transformation of systems of production, management and governance across sectors and industries in the advent of industry 4.0 has predominantly impacted the developed world, it has barely begun to be deployed in Africa. Major infrastructural, cost, and human capacity constraints still present significant obstacles to the adoption of disruptive technologies. Yet, these technologies present great potential for passing over traditional solutions to many socio-economic challenges.

This paper examined ways in which disruptive tech could potentially help improve power sector development in African countries. The paper presented technological concepts and illustrated their application with use cases in the areas of power infrastructure planning, rural electrification, and power sector operations.

The concepts behind these use cases can be extrapolated to other areas of power sector development. Some of the use cases presented here are rapidly evolving and our descriptions may need further refinement. Both on-grid and off-grid customers, for instance, could eventually benefit from blockchain technology, which—offering a secure and cheap way for financial operational transactions to be recorded and validated across the network—could, for instance, provide a more secure investment infrastructure or pave the way for peer-to-peer electricity trading (James Basden, 2017).

Scaling any of the use cases in this paper, however, requires a concerted effort across public and private players as well as development partners in addressing general infrastructural challenges, the digital skill shortage, and a multitude of regulatory issues. Industry 4.0 might not have hit the African continent quite yet, but the potential remains enormous.

References

Ashesi, n.d. *A Computer Science programme for leaders*. [Online] Available at: http://www.ashesi.edu.gh/academics/computer-science.html [Accessed 22 February 2017].

Bazilian, M. et al., 2011. *Smart and Just Grids: Opportunities for sub-Saharan Africa*. London: Imperial College London.

Bazilian, M. et al., 2012. *Open Source Software and Crowdsourcing for Energy Analysis*. Working Paper. London, UK: Bloomberg New Energy Finance.

BISA, 2017. *Google Play*. [Online] Available at: https://play.google.com/store/apps/details?id=oasis.bisa&hl=en [Accessed 2 February 2017].

Bhattacharyya, S.C. & Palit, D., 2016. Mini-grid based off-grid electrification to enhance electricity access in developing countries: What policies may be required. *Energy Policy*, 94, pp.166-78.

Blodgett, C., Moder, E., Kickham, L. & Leaf, H., 2016. *Power Productivity: Early Insights into Mini Grid Operations in Rural Kenya*. Vulcan Impact Investing.

BMZ, 2016. *Glossary—Digitalisation and Sustainable Development*. Bonn: Federal Ministry for Economic Cooperation and Development Federal Ministry for Economic Cooperation and Development.

Bright, J., 2016. *Africa's tech hubs*. [Online] Available at: https://techcrunch.com/2016/12/09/africas-tech-hubs/ [Accessed 7 February 2017].

Carbajal, J., 2015. *Nigerian Utility KEDCO Maps 10 Million Meters*. [Online] Available at: http://qsel.columbia.edu/nigerian-utility-kedco-maps-10-million-meters/ [Accessed 15 September 2016].

Carbajal, J., 2015. *Quadracci Sustainable Engineering Lab*. [Online] Available at: http://qsel.columbia.edu/nigerian-utility-kedco-maps-10-million-meters/ [Accessed 5 September 2016].

Christensen, C.M., 1997. *The Innovator's Dilemma*. Boston, Massachusetts: Harvard Business School Press.

Co-Creation Hub, 2012. *CcHub*. [Online] Available at: http://cchubnigeria.com [Accessed 20 January 2017].

Evans, D., 2011. *The Internet of Things—How the Next Evolution of the Internet Is Changing Everything*. White Paper. San Jose, CA: Cisco Internet Business Solutions Group (IBSG).

Earley, K., 2015. *theguardian*. [Online] Available at: https://www.theguardian.com/sustainable-business/2015/jun/19/phones4power-using-mobile-phones-to-run-micro-grids-in-africa [Accessed 12 November 2016].

Economist, 2015. Machine learning: Manufacturers must learn to behave more like tech firms. *Economist*, 21 November.

Efiko, n.d. [Online] Available at: http://efiko.com.ng [Accessed 20 January 2017].

Eneza Education, 2016. [Online] Available at: http://enezaeducation.com [Accessed 20 January 2017].

Essien, M., 2016. *The Hotels.ng Internship Program Recap*. [Online] Available at: http://markessien.com/the-hotels-ng-intern-program-a-recap/ [Accessed 9 February 2017].

Dahir, A.L., 2016. *The number of tech hubs across Africa more than doubled in less than a year*. [Online] Available at: https://qz.com/759666/the-number-of-tech-hubs-across-africa-has-more-than-doubled-in-less-than-a-year/ [Accessed 9 February 2017].

Deloitte, 2015. *Industry 4.0—Challenges and solutions for the digital transformation and use of exponential technologies*. Zurich: Deloitte AG Deloitte.

Deloitte, 2015. *Smart Cities: How rapid advances in technology are reshaping our economy and society*. Deloitte The Netherlands.

Deloitte, 2016. *Industry 4.0—Is Africa ready for digital transformation?* Deloitte South Africa.

Diamandis, P.H. & Kotler, S., 2015. *Bold: How to Go Big, Create Wealth, and Impact the World*. New York, US: Simon & Schuster.

Donitzky, C., Ross, O. & Sauty, S., 2014. *A Digital Energy Network: The Internet of Things & the Smart Grid*. White Paper. Intel Corporation.

Gartner, Inc., 2015. *Gartner says 6.4 billion connected 'things' will be in use in 2016, up 30 percent from 2015*. [Online] Available at: http://www.gartner.com/newsroom/id/3165317 [Accessed 14 December 2016].

Gartner, 2017. *Digitalization*. [Online] Available at: http://www.gartner.com/it-glossary/digitalization/ [Accessed 21 May 2017].

Geissbauer, R., Vesdo, J. & Schrauf, S., 2016. *Industry 4.0: Today's Most Dynamic Business Opportunity*. [Online] Available at: http://www.forbes.com/sites/strategyand/2016/05/25/a-strategists-guide-to-industry-4-0/#42e1a6165246 [Accessed 9 February 2017].

GidiTraffic, 2015. *GidiTraffic*. [Online] Available at: http://giditraffic.com [Accessed 20 January 2017].

GidiTraffic, 2015. *GidiTraffic*. [Online] Available at: http://giditraffic.com [Accessed 20 January 2017].

GSMA, 2014. *Mobile for Smart Solutions: How Mobile can Improve Energy Access in Sub-Saharan Africa*. GSMA.

GSMA, 2014. *Sub-Saharan Africa—Universal Service Fund study*. London, UK: GSMA.

GTAI, n.d. *Germany Trade and Invest*. [Online] Available at: https://industrie4.0.gtai.de/INDUSTRIE40/Navigation/EN/industrie-4-0 [Accessed 10 October 2016].

IBM Research, n.d. *IBM Research*. [Online] Available at: http://www.research.ibm.com/articles/precision_agriculture.shtml [Accessed 6 November 2016].

IEA, 2016. *World Energy Outlook 2016*. Paris: OECD/IEA International Energy Agency.

iHub, 2017. *iHub*. [Online] Available at: http://ihub.co.ke [Accessed 20 January 2017].

International Energy Agency and the World Bank, 2014. Global Tracking Framework. Washington DC, 2014. The World Bank.

ITU & Cisco, 2016. *Harnessing the Internet of Things for Global Development*. Geneva: International Telecommunication Union.

Huawai, 2016. *These smart meters are revolutionising Nigeria's power supply*. [Online] Available at: http://uk.businessinsider.com/sc/these-smart-meters-are-revolutionising-nigeria-power-supply-2016-9 [Accessed 1 December 2016].

Jackson, T., 2016. *Kenya's FarmDrive to use weather data for credit assessment*. [Online] Available at: http://disrupt-africa.com/2016/12/kenyas-farmdrive-to-use-weather-data-for-credit-assessment/ [Accessed 18 December 2016].

James Basden, M.C., 2017. *How Utilities Are Using Blockchain to Modernize the Grid*. [Online] Available at: https://hbr.org/2017/03/how-utilities-are-using-blockchain-to-modernize-the-grid [Accessed 23 April 2017].

James Basden, M.C., 2017. *How Utilities Are Using Blockchain to Modernize the Grid*. [Online] Available at: https://hbr.org/2017/03/how-utilities-are-using-blockchain-to-modernize-the-grid [Accessed 23 April 2017].

Kenny, C., 2016. *Congress Wants to Extend Gobal Internet Access: Perhaps It Could Put Some Money Behind the Idea?* [Online] Available at: http://www.cgdev.org/blog/congress-wants-extend-global-internet-access-perhaps-it-could-put-some-money-behind-idea [Accessed 2 February 2017].

Leaf, H., 2015. *Executive Perspective: Sustaiable Innovation for the World, SteamaCo*. [Online] Available at: http://sustainability.thomsonreuters.com/2015/05/08/executive-perspective-sustainable-innovation-for-the-world-steamaco/ [Accessed 13 December 2016].

Lehoczky, E., 2016. *This Startup Trains African Programmers for the Best Softwared Developer Jobs in the World*. [Online] Available at: http://www.inc.com/magazine/201603/etelka-lehoczky/andela-training-african-programmers-tech-workers.html [Accessed 23 February 2017].

Leo, B. et al., 2015. *Do Mobile Phone Surveys Work in Poor Countries?* Working Paper.
Leo, B., Morello, R., Peixoto, T. & Davenport, S., 2015. *Do Mobile Phone Surveys Work in Poor Countries?* CGD Working Paper. Center for Global Development.
LifeBank, n.d. *LifeBank*. [Online] Available at: http://www.lifebank.ng [Accessed 15 January 2017].
Natali, C., 2013. *A "WAY" FORWARD: How we streamlined power grid data collection with OpenStreetMap*. [Online] Available at: http://qsel.columbia.edu/a-way-forward-streamlining-power-grid-data-collection-with-openstreetmap/ [Accessed 23 February 2017].
Nexleaf, 2016. *Nexleaf*. [Online] Available at: http://nexleaf.org/vaccines/#what-is-coldtrace [Accessed 12 September 2016].
Mubiru, R.F.B., 2015. *Umeme*. PPT. Cape Town, South Africa: Umeme Umeme.
Mulligan, G., 2015. *How business incubators in Africa are starting a change*. [Online] Available at: http://venturesafrica.com/features/how-business-incubators-in-africa-are-starting-a-change/ [Accessed 7 February 2017].
Ma3Route, 2017. *Ma3Route*. [Online] Available at: https://www.ma3route.com [Accessed 15 January 2017].
Martin, G., 2016. *Stanford researchers use dark of night and machine learning to shed light on global poverty*. [Online] Available at: http://news.stanford.edu/2016/02/24/satellite-map-poverty-022416/ [Accessed 10 Augustus 2016].
Martinez-Cesana, E.A., Mancarella, P., Ndiaye, M. & Schlaepfer, M., 2015. *Using Mobile Phone Data for Electricity Infrastructure Planning*. Cornell University.
McKinsey & Company, 2015. *Industry 4.0—How to navigate digitization of the manufacturing sector*. McKinsey Digital. McKinsey & Company.
McKinsey Global Institute, 2011. *Big data: The next frontier for innovatoin, competition, and productivity*. [Online] Available at: http://www.mckinsey.com/business-functions/digital-mckinsey/our-insights/big-data-the-next-frontier-for-innovation [Accessed 23 April 2017].
McKinsey Global Institute, 2017. *A Future That Works: Automation, Employment, and Productivity*. McKinsey&Company.
MEST, n.d. *The MEST Story*. [Online] Available at: http://meltwater.org/about/about-mest/ [Accessed 22 February 2017].
Metering and Smart Energy International, 2014. *Metering and Smart Energy International*. [Online] Available at: https://www.metering.com/africa-insight-the-path-to-ami-in-uganda-to-curb-high-revenue-losses/ [Accessed 10 December 2016].
Metering and Smart Energy International, 2016. *Smart meters Africa: Kenya Power installs 5,600 units*. [Online] Available at: https://www.metering.com/news/smart-meters-africa-kenya-power-installs-5600-units-large-power-users/ [Accessed 1 December 2016].
M-Farm, 2017. *M-Farm*. [Online] Available at: https://www.mfarm.co.ke [Accessed 20 January 2017].
Moss, T. & Alemayehou, M., 2016. *More Than a Lightbulb: Five Recommendations to Make Modern Energy Access Meaningful for People and Prosperity*. Report of the Energy Access Targets Working Group. Center for Global Development.
Morello, R. & Leo Benjamin, 2016. *Practical Considerations with Using Mobile Phone Survey Incentives: Experiences in Ghana and Tanzania*. Working Paper. Center for Global Development.
Morello, R. & Leo, B., 2016. *Practical Considerations with Using Mobile Phone Survey Incentives: Experiences in Ghana and Tanzania*. CGD Working Paper 431. Center for Global Development.
Oxford English Dictionary, n.d. *big, adj. and adv.* [Online] Available at: http://www.oed.com/view/Entry/18833#eid301162177 [Accessed 23 April 2017].
O'Connor, C., 2015. *The Internet of Things an cloud convergence opportunities*. [Online] Available at: http://www.ibmbigdatahub.com/blog/internet-things-and-cloud-convergence-opportunities [Accessed 22 November 2016].
OECD/IAEA, 2014. *Energy in Africa today*. Paris, France: OECD/IAEA.

Office of the Vice President of Nigeria/Power Africa, 2015. *Nigeria Power Baseline Report*. Power Africa.
O'Neill, K.M., 2016. *Tata Center Technology + Design*. [Online] Available at: https://tatacenter.mit.edu/going-off-grid-tata-researchers-tackle-rural-electrification/ [Accessed 12 October 2016].
Orange, 2016. *Challenge 4 development*. [Online] Available at: http://www.d4d.orange.com/en/Accueil [Accessed 10 October 2016].
Paradigm Initiative Nigeria, 2016. [Online] Available at: http://pinigeria.org/2016/wp-content/uploads/documents/research/Digital%20Rights%20In%20Africa%20Report%202016%20(LR).pdf [Accessed 9 February 2017].
Parshall, L. et al., 2009. National electricity planning in settings with low pre-existing grid coverage: Development of a spatial model and case study of Kenya. *Energy Policy*, 37(6), pp.2395-410.
Power Africa & USEA, 2016. Ethiopian Smart Metering Workshop. Addis Ababa, Ethiopia, 2016. Power Africa & USEA.
Powerhive, 2015. *A scalable, sustainable approach to energy access in emerging markets*. [Online] Poverhive Inc. Available at: https://www.nrel.gov/workingwithus/assets/pdfs/2015-igf-powerhive.pdf [Accessed 16 November 2016].
Suri, T. & Jack, W., 2016. The long-run poverty and gender impacts of mobile money. *Science*, 354(6317), pp.1288-92. Available at: http://science.sciencemag.org/content/354/6317/1288.
Savedoff, B., 2016. *Cash on Delivery Aid for Energy*. Center for Global Development.
Saint, M. & Garba, A., 2016. *Technology and Policy for the Internet of Things in Africa*. Available at SSRN: https://ssrn.com/abstract=2757220 or http://dx.doi.org/10.2139/ssrn.2757220.
Schwab, K., 2015. *The Fourth Industrial Revolution—What It Means and How to Respond*. [Online] Available at: https://www.foreignaffairs.com/articles/2015-12-12/fourth-industrial-revolution.
Spatocco, B., 2015. *Tata Center Technology + Design*. [Online] Available at: https://tatacenter.mit.edu/portfolio/rural-mapping-and-feature-extraction-to-improve-rural-development-and-assist-in-the-planning-of-infrastructural-expansion/ [Accessed 10 October 2016].
Ramachandran, S., 2016. *Industry 4.0 manifestations in the developing world*. [Online] LinkedIn Available at: https://www.linkedin.com/pulse/industry-40-manifestations-developing-world-ramachandran-s [Accessed 24 November 2016].
Rizzato, F., 2016. *4G networks in Africa double in number, but adoption remains limited*. [Online] Available at: https://www.gsmaintelligence.com/research/2016/07/4g-networks-in-africa-double-in-number-but-adoption-remains-limited/567/ [Accessed 2 February 2017].
Telecommunication Standardization Sector, 2012. *Series Y: Global Information infrastrucutre, Internet protocol aspects and next-generation networks; next generation networks-frameworks architecture models; overview of the Internet of things*. Recommendation ITU-T Y.2060. Geneva: International Telecommunication Union.
UK Government Office for Science, 2014. *The Internet of Things: making the most of the Second Digital Revolution*. UK Government Office for Science.
UNCTAD, 2013. *Information Economy Report 2013: The Cloud Economy and Developing Countries*. New York and Geneva: United Nations.
United Nations General Assembly, 2016. [Online] Available at: https://www.article19.org/data/files/Internet_Statement_Adopted.pdf [Accessed 9 February 2017].
United Nations, n.d. *Sustainable Development Goals*. [Online] Available at: http://www.un.org/sustainabledevelopment/energy/ [Accessed 23 April 2017].
Zenvus , 2016. *Zenvus*. [Online] Available at: http://zenvus.com/products/smartfarm/ [Accessed 12 September 2016].

we_magazine, 2011. *Kenya Matters*. [Online] Available at: http://kenya-matters.we-magazine.net [Accessed 7 February 2017].
Wiki, 2016. *OSMTracker (Android)*. [Online] Available at: http://wiki.openstreetmap.org/wiki/OSMTracker_(Android) [Accessed 23 February 2017].
Wikipedia, 2017. *Big data*. [Online] Available at: https://en.wikipedia.org/wiki/Big_data [Accessed 23 April 2017].
Wirtz, B.W., Mory, L. & Piehler, R., 2014. Web 2.0 an Digital Business Models. In F.J. Martinez-Lopez, ed. *Handbook of Strategic e-Business Management*. Berlin , Heidelberg: Springer-Verlag.
Wirtz, B.W., Mory, L. & Piehler, R., 2014. Web 2.0 and Digital Business Models. In F.J. Martinez-Lopez, ed. *Handbook of Strategic e-Business Management*. pp.751-66.
World Bank, 2009. *Reducing Technical and Non-Technical Losses in the Power Sector*. [Online] World bank Available at: http://siteresources.worldbank.org/EXTESC/Resources/Background_paper_Reducing_losses_in_the_power_sector.pdf [Accessed 3 December 2016].