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Luis Munuera, Timon Dubbeling, Simon Mueller

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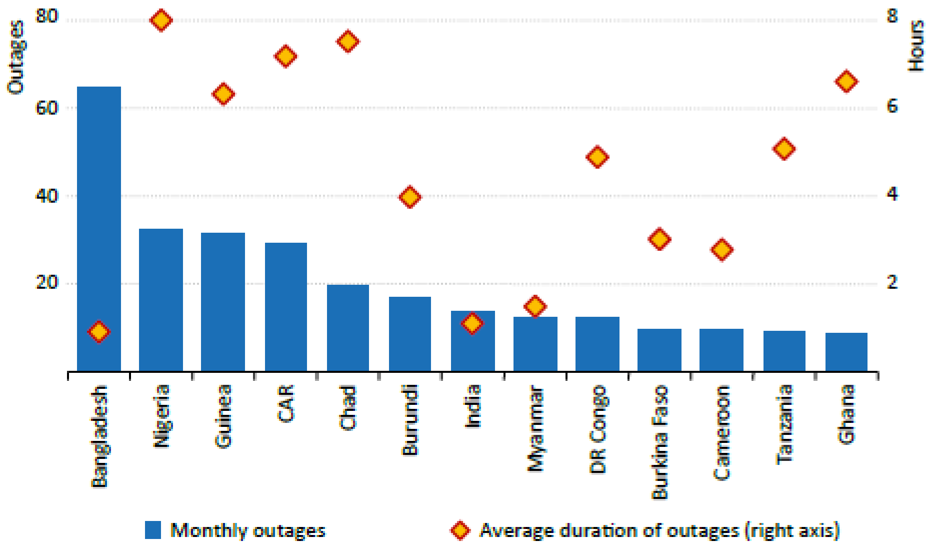
Introduction

An estimated 1.2 billion people – 17% of the global population – did not have access to electricity in 2013, 84 million fewer than in the previous year. An estimated further billion suffer from supply that is of poor quality. More than 95% of those living without electricity are in countries in sub-Saharan Africa and developing Asia, and they are predominantly in rural areas (around 80% of the world total). In sub-Saharan Africa, around 150 million people are estimated to have gained electricity access since 2000, but this has lagged population growth, resulting in a worsening picture overall – the latest estimates reveal that over two-thirds of the sub-Saharan population (634 million people) are without access to electricity. Half of these people are located in just five countries – Nigeria, Ethiopia, Democratic Republic of Congo, Tanzania and Kenya. Under a business-as-usual electrification scenario, the IEA and IRENA estimate that 640 TWh of demand from new energy access will have to be met by 2040. While still far from complete, progress in providing electrification in urban areas has outpaced that in rural areas two to one since 2000.

At the same time, major scenarios for the global energy sector project electricity demand growing between 70% and 120% by 2040 under business-as-usual scenarios (IEA 2015; IRENA 2016; IPCC 2015), with around 7 of every 8 units of new electricity demand occurring in developing and emerging economies.

Figure 1. Frequency and duration of power outages in selected countries. Source: IEA data



At the core of electrification efforts is the development of new energy technologies. Various pathways are possible to achieve both low-carbon power systems and universal energy access. Notably, however, renewable energy and end-use efficiency continue to benefit from declining capital costs (Sahu, 2015). Furthermore, the more they are deployed, the more capital costs are likely to fall. This means that, moving forward, system-level considerations --- rather than cost alone --- will increasingly constrain the transition to power systems that rely on high shares of RE and EE. In response, policy and regulatory attention is shifting to the innovations that will enable power system transformation.

In practice, this means that power systems and markets are being planned and operated in new ways. Investment patterns are also changing, flowing increasingly not just toward new generation technologies, but toward smarter grids, energy efficiency technologies, demand-side flexibility, and storage. And across the system, there is a growing emphasis on intelligent networks and innovation in power system business models.

The fundamental knowledge gap is to what extent these innovations will be deployed in developing and emerging economies, the impact they will have and the institutional and regulatory frameworks that are necessary from grid owners, operators and utilities for their successful integration (Fadaeenejad et al. 2014), which this paper aims to survey. The paper begins with an overview of these emerging technological trends, and moves on to discuss their relevance in developing countries, finally providing proposals for possible research questions.

Changes to investment, planning and operation in electricity systems

In 2015, investment in electricity networks reached a new record of USD 260 billion, with more than USD 200 billion invested in distribution grids and USD 60 billion in transmission networks. In both Southeast Asia and Africa, only USD 1 billion dollar was invested in transmission networks, while distribution networks received USD 9 billion and USD 6 billion respectively (IEA, 2016). Under the New Policies Scenario of the *World Energy Outlook*, USD 8.4 trillion will be invested in transmission and distribution infrastructure worldwide until 2040 (IEA, 2015). Asia will account for 45 percent of this amount (IEA, 2015). Decisions on how to allocate these resources have a long-term impact on the way the power system evolves, the rate of electrification and the emergence and management of grid bottlenecks.

Power system planning builds on assumptions on how the size and location of electricity production and consumption evolve over time. The value of grid reinforcement changes dynamically, and is highly region-specific. In the past, demand growth was the single most important factor driving grid expansion. Assumptions on economic growth, energy intensity and the rate of urbanization could largely suffice to plan for infrastructure additions and replacements. In Asia, the accelerating urbanization constitutes by the most important driver of the USD 1.5 trillion that will be allocated to transmission and distribution grids investments between 2015 and 2025 (IEA, 2016).

Increasingly, however, grid expansion is fuelled by a number of additional variables. From 2008 to 2012, solar PV module prices were divided by five, and solar PV system prices divided by three in mature markets due to sustained technology improvement and great economies of scale. In 2013 and 2014, module prices declined by 15-18% annually in developed markets (IEA 2014). Wind power has also seen a three-fold decline in costs since 2008. Meanwhile, distributed storage capacity doubled in 2014 (ibid). While smart grid technologies are deploying slower than expected, smart meters are reaching full-scale roll-out in a large number of markets, increasingly including emerging markets notably India, China or ASEAN countries (BNEF 2015). Finally, investment in small scale storage has grown ten-fold in five years (ibid). Taken together, these trends are increasing the modularity and scalability of power systems and opening up opportunities for the configuration of new and alternative ways of providing electricity.

Crucially, the *siting of additional generation units* has changed. Historically, vertically integrated state utilities have been in charge of both generation and transmission of power. These companies would coordinate the location of a new large thermal power plant with the state of the power grid, in order to connect the new facility cost-effectively. In the case of renewable energy technologies, the presence of natural resources determines the locations where new facilities can be built. Moreover, procurement mechanisms often prefer projects with the low generation cost, which tends to concentrate project development into regions where resource availability is optimal – particularly if the associated grid connection costs are socialized. New technologies and operational processes in California, Hawaii or New York afford opportunities to identify the best sites (Fine, 2015).

As a consequence of these cost trends, and the changes in deployment implying a shift towards smaller scale and decentralised systems, the procurement of new power generation projects can and does often occur beyond the control of grid planning authorities. Because construction and lead times – i.e. the time it takes to develop, finance, build and commission a new site – for renewable energy projects are much shorter than the investment and turnover rates of networks, it is increasingly difficult for grid planning authorities to keep up with both the distributed nature and dispersed or remote siting of renewable energy projects. In developing countries, granting of planning permits for new generation can take many months, which would indicate a re-thinking is required of traditional planning tools and approaches.

Emerging technology trends: Decentralised energy, storage and smart grids

Emerging technologies are changing this picture. Several network operators are installing voltage monitoring and state estimation throughout their distribution system. This allows for grid planning authorities to visualise where new generation should be sited. The German DSO EWE has deployed such modelling of the grid, which is able to grant planning permitting for new generation units in real time, as opposed to weeks or months of procedures.

Emergence of distributed energy resources

Of all these changes, the deployment of rooftop solar PV has been the most disruptive force of change in recent years. A combination of technology improvements, cost reductions, various degrees of support schemes and a growing preference for clean, local energy has triggered home and business owners to invest in small-scale solar photovoltaics (PV) systems. As costs continue to decline, rooftop solar PV will reach ‘socket’ parity – a situation where the cost of energy produced by a solar PV system equals the retail price for electricity – and become an appealing investment opportunity in a wider range of climatic conditions.

The *widespread adoption of distributed energy resources (DER)* is starting to play a more important role in certain power systems. DER encompass a variety of technologies that enable small-scale production of electricity and several energy services, such as demand response and the provision of ancillary (system) services. Examples of DER include small natural gas-fueled generators, combined heat and power (CHP) plants, electricity storage and solar PV on rooftops or in larger arrays connected to the local grid.

Energy Storage

Current power storage capacity is just under 3% of global electricity generation capacity (or 150 GW), and is dominated by a single technology, pumped storage hydropower (PSH). Most of this capacity was built as a cost-saving measure by traditional utilities to shift energy to help manage peak demand and to allow for the continuous operation of inflexible, baseload power generation plants. PSH plants still comprise the majority of planned deployments: 27 GW of pumped storage plants are expected to come online in the next 10 years, mainly in China, the US and Europe. Other power storage technologies comprise just under 5 GW. Battery storage however, has grown ten-fold since 2010 and doubled in the past three years. It is the modularity and the cost reduction potential of battery storage that is expected to drive growth in the technology at a similar pace (Nyquist 2015): It is estimated that the global grid battery storage market will grow from 1GW today to 45GW in 2024 (BNEF 2016).

At least four basic business models are emerging for end-user storage (Stucchi 2016). First, where an electricity grid is already in place, batteries coupled with solar PV provide end-users the ability to “self-consume” more of their solar generation, providing economic benefits depending on policy and tariff conditions. This is already being deployed in many jurisdictions where PV has seen a high penetration, including Germany or Italy, even though in many of these cases the incentive structure has not been sufficient to create an economic rationale. Second, batteries reduce (shave) the end-user’s peak power demand and thus reduce “demand charges” (capacity charges) that are based on the peak capacity over the day or month, a fundamental application in many states across the US. Third, small-scale storage (largely lead-acid batteries), can afford attractive off-grid electrification and energy access solutions, particularly where the counterfactual technology is diesel generation. Fourth, community- or mini-scale energy systems benefits greatly from low cost storage, which can greatly increase the share of distributed renewables in the system.

The question of whether end-use electricity storage and decentralised renewables make the grid redundant, and if so by when, remains open. The centralised electricity network is often referred to as a potential stranded asset, with decentralised generation and storage provoking a “utility death spiral”. While distributed technologies are facilitating a more flexible and decentralised transaction space, a robust network infrastructure, along with appropriate regulatory framework, remains a key enabler to this trend. However, under temperate climates the winter – summer discrepancy of solar production is so large (up to 200 Tesla batteries for average European household consumption) that complete disconnection from the network is not practical. The value of consumer owned batteries is enhanced if there is an ability to sell storage services back to the grid. In climates with more constant annual demands, the possibility of grid defection or remaining off the grid becomes more relevant (Fanaeenajad et al 2014).

When looking at storage applications beyond the end-user, the key opportunity for utility-scale deployment is the deferral of upgrading or expanding electricity grids. Such location-specific deployment that alleviates concrete congestion points appears to be most efficient application of battery deployment compared to a centralised, non-location optimised storage. Such batteries paired with demand side response can significantly reduce network investment needs, and are already being deployed in a number of emerging economies (DOE 2015)

Variable renewables

Wind farms are typically multi MW size and rely on a centralised grid to deliver to end users, rather than decentralised self-consumption. The direction of technological innovation for wind has been larger and larger turbines with higher hub height. In areas with higher evening, winter output, wind can have a low correlation with demand. As a result, its emergence as a major source is enabled by increased investment in networks. In the case of developing countries, scaling up wind-power, given these network needs, can often come at the cost of efficient resource allocation (Surana and Anadon 2015).

While solar PV can support small scale decentralised generation, currently large scale ground based utility scale solar farms represent the majority of investment. Those solar farms act as power plants from the point of view of the electricity network and in some cases such as Western China, the US Southwest or Rajasthan in India they require significant network investments.

Distributed solar PV deployment without storage or demand shifting is unlikely to reduce network investment needs unless there is a large midday air conditioning load (Alam et al 2013). However, even in warm climates like peak load is often in late afternoon whereas in moderate climates it is often after sunset. Peak consumption still has to be supplied from the grid whereas a very peaky midday production may have to be evacuated which might create additional network reinforcement investment needs.

Solar projects with batteries and LED lights will play a major role in both India and Africa, especially in remote areas (Mandelli et al. 2016). However, there is a rapid urbanisation in both regions, and major cities that represent up to 70% of power demand will continue to rely on a centralised system. With rising incomes, households can acquire appliances like refrigerators and washing machines with consumption an order of magnitude higher than for LED lights, though the efficiency of those appliances themselves remains an evolving variable. Some communities supplied by decentralised solar projects will eventually be connected to the centralised system.

Smart transmission and distribution grids

There are various measures to improve operations at the level of the transmission grid. When assessing the available line capacity, system operators have historically applied fairly conservative estimates for the effects of line sag, which occurs due to current-related temperature increases and determines the maximum capacity of a transmission line. Dynamic line rating (DLR) is a method for grid capacity calculation that considers the ambient temperature and other meteorological conditions such as wind speeds to dynamically assess the transmission capacity. Studies show that a gentle wind of 1 meter per second can increase line rating by as much as 44% (Aivaliotis, 2010). 50Hertz, one of the four German transmission system operators (TSOs) found that DLR increase average transmission system availability by approximately 30%. Even in the absence of renewables, DLR holds great promise for developing countries to increase network capacity without increasing investment.

System operators limit the volume of power flows to preserve a margin that can be used in the case of a contingency. Sizing this margin is usually done on the basis of the n-1 criterion, whereby the system can continue safe operations even if the largest individual element in the system is lost. As system operators usually apply conservative margins, this can be an expensive method for preserving security of supply. An alternative solution is to use a Special Protection Scheme (SPS), whereby the power system actively responds to a contingency to maintain stable operation (RETD, 2013).

Transmission switching is a technique that uses advanced modelling tools to change the topology of the power network in order to better cope with contingencies and reduce transmission losses. In practice, this means that certain transmission lines are switched off proactively to shape the path of power flows through the system. With flexible alternative current transmission systems (FACTS) or power flow controllers, it becomes possible to direct the direction and flow of AC electricity. This can also be done by converting the power to direct current (DC) which can be controlled on a point-to-point basis through a separate high-voltage direct current (HVDC) lines.

Incorporating storage at utility-scale provides a very useful tool for balancing supply and demand, improving power quality and optimizing the use of the grid. There are various technologies that can be installed at grid level, with various power and energy components. Generally speaking, storage systems incorporated at the level of the transmission network can quickly act to solve a wide range of technical challenges that might occur. Costs for battery storage have come down considerably in recent years and although it is not always the most cost-effective source of supply and demand flexibility, under certain conditions investing in storage capacity can be more cost-effective than traditional “copper” based approaches.

In distribution grids, inverters (also known as *power converter systems* or PCS) are becoming increasingly smart as they incorporate a larger number of technical attributes (Katiraei 2015). Modern inverter technologies provide a number of functionalities that support the deployment of distributed energy resources (DER) such as rooftop solar, which will be discussed in more detail in the next section. Using Volt-Watt control and volt-VAR control, modern inverters allow for voltage management at household level. Another important value comes from a number of services that provide power system support, such as active power control, voltage ride-through, as well as the ability to reconnect to the grid following a grid disturbance (black start capability). Importantly, modern inverters boast communication capabilities that facilitate monitoring and control at the level of the system operator.

Booster transformers are placed within medium-voltage (MV) or low-voltage (LV) grids and serve to stabilize the voltage along long feeder lines with dispersed consumers during times of high demand. This equipment can also serve as a solution to manage high solar PV production in local and mini-grids. “On-Load tap changer” (OLTC) equipment allows for controlling the busbar voltage level at substation transformers. Modern OLTC operation is automatic and compatible with remote control. State-of-the-art capabilities allow a system operator to measure voltage in the distribution grid and to maintain a certain voltage bandwidth using a MV/LV (medium-voltage – low voltage) OLTC. These grid control options are particularly relevant in a power system with a strong presence of small-scale solar PV (IEA PVPS, 2014).

In some regions, reactive power provision may also be challenging. Modern inverters can supply reactive power from individual systems through Volt-VAR and other capabilities, but local system operators may prefer to invest in Static VAR Compensators (SVC) to provide reactive power at the grid level. SVCs mitigate against voltage excesses by injecting reactive currents. Feeder reconfiguration can be very effective instrument for grid reinforcement. By rearranging core elements in the local power system infrastructure in light of changing supply and demand patterns, system operators can increase the hosting capacity of grids and reduce network losses (Capitanescu et al. 2015).

These trends translate into more onerous permitting procedures arising from these new technologies and the inclusion of local communities, which in turn imply the planning and construction transmission projects is becoming more time-consuming. Therefore a key strategy for enhancing grid capacity is to reinforce the existing infrastructure. Especially in areas where space is a limiting factor, there is potential value in adding equipment that can boost the capacity of existing transmission lines. In Germany, for example, the use of High Temperature Superconducting (HTS) technology has served to increase network capability (ISGAN, 2016).

Deployment of storage equipment at the distribution level can have significant benefits for the power quality, frequency management and voltage stability in local grids. With near-instantaneous response time, fast-acting storage equipment can deliver important technical capabilities to the grid. Local system operators are increasingly looking to adopt storage solutions. The cost-effectiveness of local storage is subject to rapid technological and regulatory changes and must be assessed on a case by case basis.

More importantly, these technologies for power system monitoring and control technology have enabled in developing countries a departure from traditional deterministic “N-1” power system planning, whereby the system is designed to continue safe operations in case the largest individual item in the grid is suddenly lost. This method is considered relatively conservative in terms of the amount of transmission capacity that remains unused for contingency reasons. Instead, power system operation, and cross-border interconnection capacity allocation is increasingly driven by ‘flow-based’ optimizations, whereby the available grid capacity is calculated using the real-time status of critical grid components. However, at the moment there are significant gaps in the literature as to the costs and benefits of smart transmission and distribution grid technologies in developing countries, signalling an important area for future research.

Shift from passive to active distribution networks

The emergence of such DER and smarter technology options changes the distribution grid from a “passive” or “collection” grid, which merely serves to connect large centralized power stations to the different electricity customer, into a dynamic arena where a vast amount of smaller appliances causes bi-directional power flows. This change forces a rethinking of the investments and operations in power grids.

The rise of DER has gone hand in hand with the exponential *increase in data* in the energy system. Advances in data collection and management tools can provide more accurate information on the status of grid components in real time. The prevalence of data is perhaps the single most valuable opportunity to improve grid planning and operations. At the same time, traditional system operators and planners will need to invest in the necessary tools and skills to obtain and manage these data flows effectively.

The combination of these changes has made grid planning vastly more complex. Expanding the grid traditionally lags behind other forces shaping the power system: the pace of supply and demand deployment, and the progress of technologies used, can exceed the ability of grid planners to develop new infrastructure. As monetary and energy flows evolve quicker and in a more dynamic fashion, and as public consultation plays a larger role in the planning of new power lines, the discrepancy between the identified need for grid reinforcements and their realization may become increasingly relevant. Grid planning methods, particularly in a regulated utility environment, will have to account for these changes, and find an appropriate trade-off between short licensing procedures and the long term lock-in effects that any power line can provoke (Turner et al. 2015).

Digital energy

The rapid spread of digital technologies in recent decades has fundamentally transformed the way modern societies get access to goods and services. To date, however, the tools and instruments that are used to maintain safe grid operations have remained predominantly analog. This is slowly changing as modern power electronics and state-of-the-art ICT solutions are used to improve the design and operation of power systems. Improved data mining and analytics combine with intelligent control equipment to foster a more resilient power system.

A digitization of power networks can support the planning process, as more precise data support the timely identification of key present and future bottlenecks. As grid expansion is a highly complex, time-consuming process and capital-intensive undertaking, precise data is of vital importance for effective decisions and an optimized use of limited financial resources.

Data flows can be utilized to inform power system infrastructure decisions. In many OECD countries, distribution grid planning is starting to be carried out at a level of granularity that allows for data analytics to assess the attractiveness of individual projects, the impact on the grid and to grant new permitting in the space of a few hours (instead of weeks or months). Practical examples include the real time distribution network modelling capacities from EWE in Germany, or large-scale pilot projects such as Nice Grid. At the same time, 'big data' is allowing specific incentives to be tailored to individual end-use consumers in various jurisdictions.

Challenges and opportunities for alternative power systems in developing and low-income countries

The trends outlined above open up new possibilities for moving away from centralised, top-down planning of grids and generation based on aggregate forecasts for demand, towards more decentralised energy provision and a modular, bottom-up build-up of power grids. These trends alter the economics of microgrids, minigrids, self-generation and modular build-up of electricity networks. In the absence of legacy systems, many developing countries have the opportunity to leverage decades of technological advancement and experience in developed countries as they build innovative modern infrastructure systems. While there is much interest in the possibilities for leap-frogging in electricity systems, the research literature shows few techno-economic assessments trading off different approaches towards grid build-out in a developing country context.

In much of the developing world, particularly in Sub-Saharan Africa, rural electrification is already being pursued by a combination of grid extensions and micro-and mini-grids, or solar home systems providing low-voltage direct current electricity to meet demand for small loads. These countries, given the diversity of loads and infrastructure in developing countries, can serve as test-beds for many smart grid and distributed generation concepts. Power provision in most developed countries carries a level of system security, reliability and adequacy that translates to 24/7, high quality supply of electricity. This level of service does not reflect the immediate needs of much of the developing world. At the same time, this dearth implies customers in developing countries typically have a much higher awareness of their energy use and the issues associated with intermittent energy supply. Consumers in these context are much more likely to adopt sensing and monitoring technology (Brown et al. 2013), opening the possibility for micro-mini-grids or stand-alone systems, and radically different technological solutions.

The electricity required to charge cellphones, PCs or provide lighting is generated locally. Technologies such as micro-or mini-grids or small scale renewables co-exist with legacy systems. Crucially, the smaller scale implies access to ICT technology, which can increase the profitability of distributed energy business models, including those based on more rudimentary technology. Thus in the current developing country context local generation takes a central stage.

The following sections aim to highlight technologies, strategies and policy frameworks that could foster the development of power sector infrastructure in alternative ways that reduce the costs of transitioning to decentralized, renewable and low carbon energy sources. The resulting insights can be of particular relevance to lower income countries (LICs), which often display a need for additional investment as well as a growth in modern, clean energy generation technologies.

Microgrids and mini-grids

Microgrids are localized grids that can disconnect from the traditional grid to operate autonomously and help mitigate grid disturbances to strengthen grid resilience.

For inhabitants of urban areas access exclusively via grid extensions is generally the more economical option. Households close to areas of relatively high population density, i.e. in and around the centres of villages, tend to gain access through the grid as well. In both cases however, microgrid configurations have important benefits, and are already being deployed in urban areas in a developing country context (Williams 2015). The generation in a microgrid can be utilized to mitigate the impacts of large scale grid outage on the critical functions of the microgrid owner. These are particularly valuable in military installations, research laboratories, universities, data centers or banks which need for their operations to not be impacted by disturbances in the grid. While the level of service is different (and thus the resilience built into micro-grids), de-facto micro grids are widespread in developing countries, arguably as a response against high interruption durations and frequencies. While these systems used to rely on diesel generators, advanced microgrids are now being utilized to save costs and increase resiliency.

Where grid extension is technically difficult or more costly, mini-, micro-, or off-grid solutions are an emerging option. However these face some important difficulties. Low tariffs for on-grid supply, which may often lie below appropriate cost-recovery levels and not reflective of actual conditions, can create difficulty for emerging technologies and business models. These measures, coupled with uncertain grid extension policies, can bias the economics of off-grid micro- or mini-grids. Mini-grids are a potential source of greater levels of electricity supply, and can be powered by renewable or oil-based sources, or a combination of both. Hurdles for mini-grids remain, including affordability, with potential customers unable to afford appliances that consume enough power to make projects economic. This can be compounded by battery costs, lack of expertise and a lack of financing for a system that is still considered risky (Datta, 2014). The design of policies to increase energy access with off- and mini- grid renewables can already benefit from past experiences. They should take into account communities' present and future energy needs, use quality materials, develop a skills base for operating and maintaining new systems, and ensure systems are affordable, including providing financing to help cover the high upfront costs of renewables.

IEA scenarios estimate that to achieve universal access to modern energy, 60% of the capacity additions to deliver electricity access are mini- and off-grid systems in rural areas. Once access is achieved, expansion of mini-grids is a key area of focus, as the standards, capacity and demand trajectories required for future connection to a central grid are not necessarily interoperable, and risk stranding assets or inflating the cost of electrifying rural communities.

Today, mini-grids are community-based projects or social enterprises. Private sector innovation is increasing, with new models such as fee-for-service. While this is promising, private investors tend to invest mainly in areas where consumers have the ability to pay without subsidies. Targeted support for small-scale projects remains essential.

Local capacities also need to be appropriately developed (Williams et al 2015). Technically, micro-grids can be more difficult to control than larger grids – for instance, voltage surges and sudden increases in frequency can occur from starter motors, and in general they need forms of back-up power or demand flexibility. In India for instance, mini-grid developments proved to be successful because provision was made for the involvement of qualified technicians to support the local level operators. In other areas, a cluster approach involving structured maintenance networks, using (as far as possible) standardised systems has been adopted to reduce transaction costs (Palit, 2014).

Defining the respective roles of on-grid and off-grid technologies is important to achieve faster progress with electrification, as is the existence of an integrated and well-coordinated strategy among the various public bodies involved. The affordability of power for the poorest households is an essential criterion if electrification is to bring sustained benefits in terms of welfare:

metering, differentiated tariffs and better targeted subsidies for the poorest households can all help in this respect. Building in provision for electricity to support productive uses, i.e. for small businesses, can also contribute strongly to financial sustainability, as these businesses become an important source of economic activity and revenue.

Solar home-systems

While the off-grid power market is still in initial phases of development, accelerating sales and investment suggests the beginning of a market transformation. In 2015, an estimated $276 million was raised by off-grid solar companies, 58% of which was raised by Pay As You Go (PAYG) companies (REN21, 2016). By 2016, one such company, M-KOPA, had sold more than 280 000 off-grid solar packages (which combine a small solar panel with several LED lightbulbs, a mobile phone charger and radio) to homes in Kenya, Tanzania and Uganda. The PAYG business model is an innovation that allows customers to pay a small upfront cost and (using mobile payments) lease the equipment over a number of years at a smaller cost than they would pay for kerosene lighting. The acceleration of sales in these solar packages has largely been down to better affordability, helped by the PAYG business model and the falling costs of solar technology, and more efficient appliances that allow the solar panel to be smaller. The potential for rapid scaling and wide deployment of solar lamps and such small solar-powered systems is huge, and beginning to happen. The level of energy service provided by such systems, while a great improvement on the current situation for many is, however, limited to low-powered appliances. Larger-scale solar home systems (SHS) use bigger solar panels, but can power additional appliances such as televisions, pumps and fans. In Bangladesh, around 4 million SHSs have been installed and the government plans to increase this number to 6 million by 2017 as a key part of its plans to bring electricity to every household in the country by 2021.

Costs of such systems may be further cut through the implementation of (DC) micro-grids, especially when combined with photovoltaic generation. While losses can be reduced through saving layers of DC/AC power conversion, the more expensive protective devices required for fault management and control, such as coordinated power converters, add complexity and outweigh some of the potential savings.

The key challenge however is scalability – these decentralised options have a low load factor, and high overheads. Here finding new business models, standards and interoperability are key, and how to ensure connection to grid occurs at a low costs. Examples where this is currently being achieved include Bangladesh and Malaysia (Friebe, 2013).

Data-driven grid planning and operation opportunities

Earlier sections have shown how data flows can be utilized to inform power system infrastructure decisions. In many OECD countries, distribution grid planning is starting to be carried out at a level of granularity that allows for data analytics to assess the attractiveness of individual projects, the impact on the grid and to grant new permitting in the space of a few hours (instead of weeks or months). At the same time, 'big data' is allowing specific incentives to be tailored to individual end-use consumers in various jurisdictions.

The most common planning is applied for the static expansion of primary distribution system, and the variables include the integrated optimization of the location and size of substations and feeders. Generally, the objective is the minimization of the total fixed and variable costs. Increasingly however, these are evolving to cover attributes of the active distirubtion grids outlined above: load control, automatic switching, or integration of distributed generation (Georgilakis et al. 2015), which require data-driven planning and operation. In thise area, key opportunities for developing countries are grid analytics and predictive maintenance and leakage management (Fadaeenejad 2014).

Grid analytics supports near real time analysis of the grid to improve grid stability and effectiveness and prevent outages. This is particularly effective in smaller grids or in grids in remote locations, including many of the micro- and mini-grid topologies being deployed in developing countries (Jimenez-Estevez 2014). It requires correlation analysis, for example to understand under which circumstances specific equipment for example a transformer is overloaded, and forecasting capabilities to predict peak loads. The analytic results are required to trigger manual interactions or other systems that actively control the grid assets. This process heavily relies on sensor and event data from the grid, but meter data is required as well. The solution provides most benefit if the data and analysis, is available in near real time that means a couple of minutes or even seconds after receiving the data, to enable rapid actions.

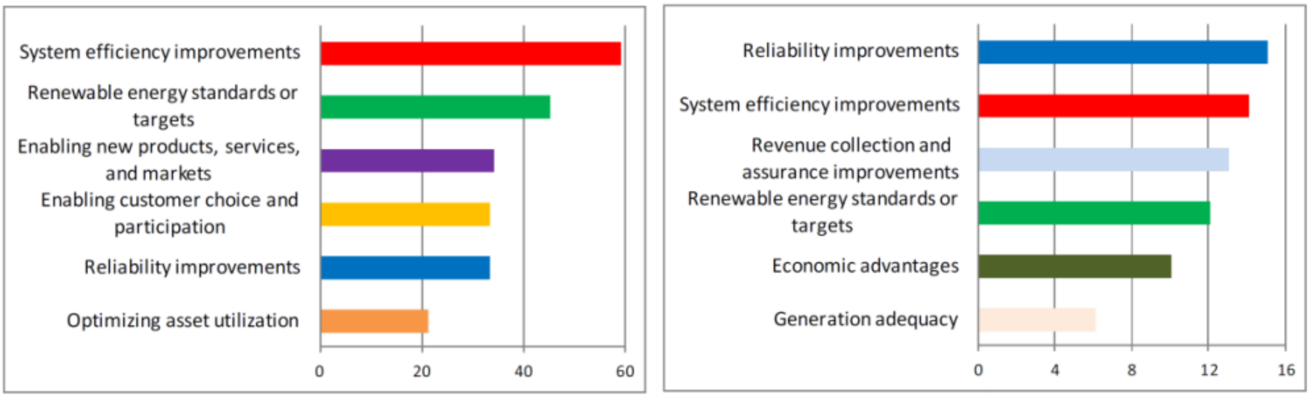
Predictive maintenance predicts when a failure or decrease in efficiency of an asset is to be expected and triggers maintenance actions accordingly. This is based on meter and sensor data as well as on historic values. Predictive maintenance is in general of interest for grids and power plants, but especially for assets in remote locations like off-grid systems, remote power plants or secluded transmission facilities.

Leakage management supports processes like fraud management and an early detection of technical losses. It contributes to determine where losses occur and if fraud could be the cause and acts as a starting point for follow up processes. Increasingly revenue collection and assurance are emerging as a key driver for smarter grids in developing countries, vastly different to those in developing countries (ISGAN 2014).

When compared to those of developed countries, the vastly different needs for ICT applications in developing countries of improved grid stability and outage reduction; predictive maintenance for micro- and mini-grids or isolated communities; and leakage management to ensure revenues, indicate that ICT and smart energy technologies require different designs, specifications and technical standards when compared to those in developing countries (Figure 2, and Welsch et al 2013).

Of the technologies highlighted under the ‘Smart transmission and distribution’ sections, vast gaps exist in the literature as to the cost-effectiveness of these in a developing country context. Several reviews highlight the need for more research in the cost-benefit of these in such environments (Fanaeenejad 2014, Williams 2015, Welsch 2013), and in developing methodologies themselves that take into account in a transferable way the benefits in weak or underdeveloped grids (e.g. the higher value of marginal increases in quality of supply). It should be noted that even in developed economies, cost-benefit methodologies for smart distribution and transmission technologies is often ad-hoc and not consistent.

Figure 2. Global drivers for smart grid and digital energy technologies in developed (left) versus developing countries (right). Source: ISGAN 2016. **Note: Units are dimensionless and reflect the result of a cluster analysis**



Coordination between generation and transmission in developing countries

As discussed above, there is often a temporal mismatch between the expansion of generation assets and the speed of grid infrastructure build-out. This is particularly aggravated in a developing country, where institutional alignment and local capacities may be weaker (Martinot 2016). Moreover, additional generation projects use a more diverse set of technologies, and are often connected at lower voltage levels. Whereas faster permitting can help reduce this discrepancy, trends in distributed energy, renewables and policies that increase electricity access increase the complexity of planning at the local level. In developing countries, where new generation capacity is needed to accommodate a growing demand for energy services, smarter planning consists of designating priority zones where the grid will be strengthened *ex ante*. In combination with other incentives such as project-specific tenders or a sharing of grid connection cost, project development can then be directed towards these zones. Even if this implies that new capacity is developed in sites with lesser natural resources, the reduced per-project grid reinforcement cost may increase the benefit to the overall power system (Arasteh 2016).

Box 1: examples of integrated planning efforts:

In South Africa, renewable energy projects are procured on the basis of competitive technology specific tenders. Because the procurement program does not include geographical factors, renewable energy projects have concentrated in areas with the most favorable resources. This has made it difficult for state-owned utility Eskom to effectively plan for the grid expansion that are necessitated by the roll-out of these new projects. In 2015, the department of environmental affairs has published designated of Renewable Energy Development Zones (REDZ), where transmission expansion will be prioritized.

In 2005, the Public Utility Commission of Texas (PUCT) was ordered to designated five competitive renewable energy zones (CREZs) where projects using renewable energy would be developed. In addition, PUCT ordered specific transmission improvements that would connect these CREZs to load centers across the state of Texas. By anticipating transmission infrastructure to connect over 11.5 GW of wind power to load centers, and spreading the associated cost across all electricity users, the state thus overcame the chicken-and-egg problem that transmission lines often face while lowering the overall cost of generation and transmission expansion.

In Ireland, a rapid increase in the number of licensing applications for wind projects triggered the use of a “gate” system, whereby several applications would be grouped according to their project location and assessed for grid connection together. This procedure assists the system operator in planning for connection procedures in an organized, systematic way. In addition, the “gate” process allows for control of the pace of renewable energy capacity additions in line with clean energy technology objectives.

Potential areas for future research

What is a best practice methodology for a low income country to develop a balanced approach between interconnection, upgrading national grids, and decentralized energy solutions?

Studies considering the trade-offs between these options for providing access to electricity and demand growth are carried out on an individual basis. Often, these rely on levelised cost of energy assumptions that are not consistent, reflective of local conditions or transferable to other contexts. However, given the proliferation of GIS information at the global scale, including information on transmission and distribution infrastructure, solar and wind potentials, power plant locations, and location of demand centers, there is a need to develop a consistent methodology for evaluating the conditions under which interconnection, local grid upgrade or decentralized solutions should be selected.

Harmonising methodologies for the techno-economic evaluation of microgrids at a national level would also bring important insights. Institutions such as the IEC or ISO could be involved in a study to develop a 'standard design' for microgrids, and the cost components and other cost items in a levelised cost calculation could be sourced locally to develop a benchmark for the technology in the country, and understand which capacities need to be developed to reduce the cost of these projects. In order to make these transferable between jurisdictions, the methodologies developed would have separate those cost components that depend on global technology trends (e.g. modules or related equipment purchases), and those that are local in nature (e.g. transportation, local labour and customer acquisition, balance-of-system costs). This would have great value for local policy-makers, who often need to rely on individual project developers or auctions to reveal costs of these options – in contrast with grid-related expansion, which tends to inspire more confidence as the costs are with a utility and are more transparent. Such a document would rely on existing data from IEA, IRENA, WTO, World Bank and other organisations and could serve as a benchmark to bring stakeholders together and develop an integrated and well-coordinated strategy among the various public bodies involved.

What are appropriate designs for smart grid end-use and distribution network technologies in developing and low-income countries?

The applicability of smart grid technologies is beginning to be understood in OECD countries. The European Union or the United States have developed cost-benefit analysis to evaluate which technical investments result cost-effective within their jurisdictions. However, the existing CBA methodologies take into account a developed country perspective, where consumer involvement is low, access to and cost of capital is reduced, and reliability and safety standards are high.

To date, there is no consistent assessment of the design requirements of ICT and smart grid technologies in a low-income country context. Standards specific for technologies for energy access in developing countries are critical – particularly considering the benefits of low maintenance equipment to ensure long usable lifetimes, or the difficulty of financing high capital cost technologies.

A key area of research here is addressing standards and appropriate designs that solidify the levels of interoperability required to expand networks in a bottom-up fashion from the very low loads of solar home systems or small-scale micro- and mini-grids, to scaled-up local networks and eventual connection to large-scale regional or national grids. At the moment, the requirements for these procedures are unknown and the lack of international standards for such interconnections could greatly increase the long-term cost of grid development in countries adopting renewable or decentralized electricity system build-outs. A practical recommendation would be the development of a database that collects the standards from ISO, IEC, IEEE and other bodies currently in use in a development country context and applies it to different technology configurations in a platform that is open to the public. This could take as a benchmark the IEC smart grid standard roadmap, where users can navigate a 'virtual' grid and understand which standards interact with each other and which do not.

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