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Author

Modi, Vijay

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Vijay Modi

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Reducing Generation, Transmission and Distribution Inefficiencies and the Feasibility of Low Voltage Supply in LICs

Vijay Modi, Professor
School of Engineering and Applied Science and the Earth Institute
Columbia University
New York, New York 10027

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Abstract

The paper addresses the issue of reducing generation, transmission and distribution inefficiencies in the context of low-income countries (LICs). Here, inefficiencies include both those arising from technical and non-technical reasons. The paper also looks at the impacts of these inefficiencies on creating an enabling environment for attracting financing and investment for the utilities, and how technologies that enable tighter technical and financial auditing and lower transaction costs in payment and verification systems, could assist. A bottom-up approach using prepaid metering at the consumer end, or conventional metering with audit capabilities, automated feeder or distribution transformer readings, might allow a utility to both better manage quality of supply, identify losses, create accountability metrics, and support tighter revenue collection. In a future generation mix with variable renewables, "flexibility" will play a larger role, and looking at how integration would occur with increasing electricity demand in LICs, regional versus local approaches, emerging cooling and heating loads, and likely electrification of transport fleets. Lastly, this paper addresses what research needs to be done to address prioritization of investments in electricity provision in order to remove energy as an impediment to specific sectoral (e.g. agriculture, industry, services) growth plans.

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Introduction

Reducing generation, transmission and distribution inefficiency has been recognized to be one of the key ingredients in the future shape of the electricity sector. These efficiencies will work in tandem with appliance efficiency improvements. Moreover, a large shift is also anticipated in the transformation of the transport sector from internal combustion engines to electric engines, from fuel based space heating to heat pumps, along with greater reliance on variable sources of energy fed into the grid. So these factors together will impact shifts in load factors, new and retiring sources of generation and associated efficiencies.

The paper will articulate the need to examine the interaction between:

- improving efficiency in generation, transmission, distribution
- technical and business architecture for metering
- appliance efficiency
- commercial losses
- utility institutional and management structures
- transaction costs of payments, collection in LIC
- financing and utility credit worthiness

These aspects are inter-twined and need to be looked at holistically. Given these linkages between technical, business, commercial and social, rigorous research has been difficult. However new designs and architectures that leverage internet of things, measurement technologies, payment systems, data and what we know about how institutions and incentives work can suggest novel approaches for paradigms that address several linked issues simultaneously.

A broad but brief engineering background is provided first. There is no attempt to be comprehensive or precise in the engineering sense. Instead the objective is to highlight and allow linkages with non-engineering issues to emerge so that one can tease out where future studies could have impact. There is an attempt to limit the context to those issues where we see particular relevance to low-income settings and try to seek technologies from a cost-effectiveness perspective. Next, we provide a discussion of losses in various stages of the process from generation to the end-user.

The paper also seeks out institutional, policy and political-economy factors that might lead to commercial losses beyond the technical losses. Separating these and even assembling the data for different utilities, and their associated institutional structure would be important. While not within scope here, that would be important to understand aggregate losses that are sometimes as high as 40% in many of the utilities or distribution companies in poor countries. When combined with tariff structures that are sometimes kept artificially low, leads to a situation where the utility is never credit-worthy and lacks the ability to make investment in reducing losses. There are also going to be differences between how a purely private utility is operated and how a fully or partially government owned parastatal entity is operated, especially in settings where independent oversight institutions, regulatory bodies, accounting practices and enforcement are possibly weaker.

The possibility of dramatic improvements in the efficiency of end-use appliances and lighting, are not the subject of the paper as such. However, if one takes the viewpoint of delivery of "*energy services*" as opposed to delivering kWh, then one can imagine that the overall efficiency chain is from an energy source to energy services and not just from an energy source to a unit of electricity delivered to the consumer. Where access is a challenge, these efficiency gains need to be realized in low-income settings along with cost-effective expansion of access. Infrastructure is required for the combined needs of growth and change in consumption in poor countries and as a result large investments will be needed even in access alone (e.g. IEA (2012) has estimated the need of investment of nearly $979 billion). These needs will only be met if public finance will be efficiently deployed and leveraged to enable private and other capital (e.g. from sovereign funds, pension funds, and borrowing from the market).

Hence, whether what is delivered is billed by kWh or by service, we need to be cognizant of the possibility that the scaling of a new paradigm leverages the combined gains from both technical and commercial loss reductions. We have in our own work shown that the consumer, even a poor consumer, is actually credit-worthy even though the lack of credit-worthiness of the intervening utility or service provider has led to poor expansion of service and poor quality of service. Clearly radical transformations will need further examinations and the dimensions of such a study are articulated.

Background

What is Efficiency?

The notion of efficiency needs to be understood in the context of this paper. Efficiency in thermal generation (e.g. coal, natural gas, liquid fuels, nuclear) is primarily a matter of design[1] and to a lesser degree a function of operation. Even operation at off-design conditions, due to part-load of load following the penalty in efficiency is a matter of design. Efficiency in thermal power generation was of particular interest because it directly impacted the cost of fuel which over the lifetime was the dominant cost of operation. For example, cost of natural gas can start to exceed the capital cost of a gas turbine power plant in less than two years of operation. Moreover, efficiency in thermal generation also impacts emissions per unit of electricity produced. Geothermal power plants can have lower efficiencies due to lower maximum temperatures (compared to fossil fuels)

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[1] The term efficiency of a power generation plant, arose primarily in the context of centralized thermal power generation, where it referred to the fraction of heat (a form of energy) that was converted to electricity (also a form of energy but a more useful one). It has ranged from 30% to 45% in single-cycle power plants (whether coal or natural gas or liquid fuels, or heat from nuclear fission) to as high as 60% in natural-gas based combined cycle power plants. In the case of geothermal power generation efficiencies can be even lower but less of concern as source of heat is renewable.

but since there is no cost of fuel, the choices are frequently dictated by upfront costs alone and efficiency is something that is limited by what nature provides as a resource.

In solar photovoltaics, efficiencies refer to conversion of energy in the sunlight impinging the solar module to electricity. For single junction cells, these have increased from around 10 percent to 15 percent today with best in class cells achieving closer to 20%. An increase in efficiency from 10% to 20% could halve costs of land, land preparation, steel structures and concrete footings. Without going to multi-junction cells, it is not possible to carry out a further doubling from 20% to 40%. But those cells are so much more expensive that to manufacture that it is difficult to imagine justifying those costs with reduced balance of systems. For wind power, the efficiencies of conversion (from kinetic energy of wind contained in the cross-section area of the wind turbine to electricity) at optimum design wind speeds are around 45% (this is nearly 75% of the theoretical maximum). So in the sense of conversion of wind to electricity, the technology is quite mature. However, given the range of different wind speeds one encounters, the operation of the turbine is nearly always at sub-optimal. The industry continues to improve performance through higher hub heights where the winds are stronger and going offshore where winds are sustained and one is closer to where the loads are.

Sub-optimal performance of a solar cell (because it is cloudy or it is simply past sunset) and wind turbines (because the wind is weak, or not blowing at optimal speed or blowing too fast) is today primarily determined by the nature of the solar and wind resource. Since costs are generally proportional to peak generation capacity (to first order, even though as we have seen the overall installation costs do reduce with increasing efficiency), the critical metric of performance is not efficiency of conversion, but the capacity factor, which is the ratio of energy produced over the year to the energy that would be produced if the optimal resource conditions were to be present over the entire 8,760 hours of the year. The capacity factor for solar PV and wind turbines are strongly dependent upon the resource and hence on geography, time of year and diurnal variations of the resource. Under ideal conditions (where the sun shines bright and clear year round for solar, and strong steady off-shore winds averaging 8 m/s or more) these capacity factors can be 25% and 50% for solar and wind respectively. In more typical installations they are about half that. With generation costs getting lower, increasing supply needs larger land (or offshore) areas with quality resource. Costs and losses in gathering and transmitting the resource over long distances does become important. The good news is that the marginal costs as well as losses of transmission with HVDC are lower compared to AC at long distances.

In case of say hydropower, the upper limit is not limited by thermodynamics and conversion from potential energy of water to electricity is 80 to 90%.

Efficiency in the context of a transmission and/or distribution lines is the ratio of electricity delivered at the customer meter to the electricity generation fed into the system. Including losses of the up and down conversions, systems are designed (with appropriate voltage, conductor area and distance standards) so that these efficiencies are above 90% or losses are less than 10%. In countries where rural electrification takes the grid to places with long lengths of wire and primarily residential loads, distribution losses under least-cost design principles can be higher. It is worthwhile in future work to understand how these differences in design and loads impact losses.

Transmission and Distribution Systems:

In the case of transmission and distribution systems from an intended design perspective all the combined energy losses between busbar at generation and the customer meter should be less than 10%. Developed countries do achieve this level of efficiency. Indeed they have had: (i) decades and sometimes a century of experience with grid infrastructure and its maintenance, (ii) high demand densities and flatter consumptions levels with a diverse mix of loads and (iii) high investments in maintenance and reliability along with high customer (or public service commission) acceptance of the distribution costs and finally iv) well-developed oversight, reporting, tracking, financial and regulatory systems.

What precisely are the losses in the Transmission (T) and Distribution (D) system would depend upon the spatial topology, standards adopted, loads, distances and specifications of the transmission (132 kV and higher) and distribution lines (generally 66 kV and below), sub-station and distribution transformer sizing, specifications, and the nature of loading of all of the above elements. For good reasons and capex constraints, the losses could be higher in LICs since upgradation is delayed, geography might dictate long feeders, peaky loads, imbalance in phases with uneven growth across phases and overhead of keeping transformers energized even at low loads. So to a degree, higher technical losses are not unexpected.

On the commercial or non-technical side, one would expect that there is no theft or pilferage from wire, accurate metering, no billing irregularities due to either technical reasons (e.g. malfunctioning meters) or non-technical reasons (e.g. tampering, theft, or simply inability of the utility to meter everyone). Moreover, one would also expect that close to 100% of the billed amount is recovered by the utility from the customers. This is however not always the case. Note that all losses not associated with technical losses are sometimes called commercial losses. The combination of the two or **A**ggregate **T**echnical and **C**ommercial (ATC) losses go by the acronym of ATC losses.

Hence in the case of the entire T and D systems, it is worthwhile considering the following taxonomy of losses.

Technical Losses

- Losses from step-up transformer, through the transmission lines (assumed to be higher than 69 kV) and up to step-down substations to medium voltage (MV) lines (assumed to be from 600V to 69 kV[2]), through the medium voltage wire to one or more step-down sub-stations/transformers that takes electricity from MV lines to low-voltage or LV levels (600V or below). The losses here are primarily technical since illegal tapping along this portion of the system would be difficult to execute since it would be large scale, visible and involve significant

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[2] Note that in some countries the distinction between MV and LV might be made at 33 kV, i.e. anything higher than 33 kV might not be considered MV.

technical and financial investment on part of the entity trying to steal. Here generally the tradeoffs have to do with making investments in larger transmission voltages and conductor sizes (and hence higher initial costs for transmitting same amount of power), as opposed to larger recurrent losses with lower voltages and smaller conductors.

- Note that here LICs may be impacted differently since their capital costs as well as load growth rates might be different from developed economies, whereas the technical knowledge might emerge out of consultants/firms with developed country experiences. Voltage conversions, upsizing or reconfiguring secondary networks, adding parallel feeders, changing transformers are some of the options for loss reductions.
- Technical losses from the low-voltage distribution transformer to the customer premises. Here some of the customer side inductive loads might add reactive power and increase losses. Here power factor correction measures might be needed. Increased loads over time, might also imply undesirable voltage profiles along the feeder length and might need measures to flatten the profile.
- Of particular importance is the need for phase balancing. In LIC settings where loads are emerging/evolving balancing phase currents along three phase circuits is critical. Line losses can rise sharply as the percentage of phase imbalance increases.
- Overall improvement in system reliability would be just as important and some of the measures might include replacement of obsolete protection gear, inspection/installation of equipment such as auto reclosers, and auto load-break switches and sectionalizers in the distribution system.
- Possible technical losses in metering where the technical loss is due to some malfunctioning on meter side without explicit tampering or fraud.

Losses in wire can primarily be due to losses arising from conductor resistances, possible temperature effects, unbalanced loading, joints/terminations and losses due to low power factors. In addition to resistive loss (or called copper losses), transformer losses can include eddy current and hysteresis losses.

The above discussion becomes particularly relevant in LICs where loads are growing differentially in different areas and so stresses are emerging on the technical side, but the way the utility financing and targets are structured are perhaps for bringing connectivity to new areas, for new power plants, new transmission lines and new customer connections. Hence manpower and resources for managing the existing system may be lacking. A research question is whether low tariff recovery and low budgets for maintenance are actually counter-productive to the entire system?

Non-technical or Commercial Losses

- While bare conductors in distribution lines save money, they are particularly prone to electricity theft and pilferage given the ease with this practice is carried out in spite of the obvious risks[3].
- Large number of connections simply not legal in the sense that they are not registered, metered and billed by the utility.
- Non-technical losses arising from tampered/ bypassed meters or other means to avoid being billed for consumption such as collusion between meter reader and consumer or multitude of factors than can result in poor accounting/audit and hence lack of detection of errors.
- There can also be commercial post-billing losses due to billed amounts not paid and a lack of system to identify and address defaulters.
- There are additional overlooked sources of commercial losses. Well-intentioned (or otherwise) subsidies could create possibility of taking unfair advantage of the subsidy. For example, subsidized electricity intended for agriculture pumping could be utilized for other non-agricultural loads creating a commercial loss for the utility.
- Flat rate un-metered tariffs for irrigation and agriculture create an opportunity for unaccounted losses in the rest of the system.
- It may be that the utility is required to provide electricity to municipalities or some other sector of the government and yet it may be not possible for the utility to easily recover associated amounts due to weak systems within governments and political pressure from local bodies to not turn off service that aids public and social infrastructure.
- A challenge with such a situation is that it actually makes it difficult for utility management to carry out effective accounting and audits and that creates a setting where utility staff are either lax to stop commercial losses or tolerate theft and fraud for private gain.
- An additional overlooked source of financial loss that is particularly worth examining in much greater detail are: (a) transactional cost of meter reading, data entry, generating and delivering a bill and the cost associated with receiving and recovering payments, and; (b) high operational and maintenance staffing costs relative to metrics such energy sold or customers served. This last aspect can partly be addressed through training and technology especially if both the consumer base and loads are anticipated to grow.

Worldwide losses are quite concentrated in Latin America and India (Jimenez et al, 2014). Within much of Sub-Saharan Africa, the absolute amount of losses are lower due to lower absolute consumption, however shown in the graph below, the percent losses are not small (IEG Report, 2016) as shown in Figure 1. The picture would be no different if all the States of India would be compared. In India losses of 40% were not uncommon until recently even though there are some States that did much better. Moreover even in the poorer performing States these have come down in the last five years. Here total systems losses include both the technical and commercial losses, or are together called ATC or Aggregate Technical and Commercial losses. An excellent brief overview of the Indian context is provided in a recent piece by Tongia (2015). The article talks about the

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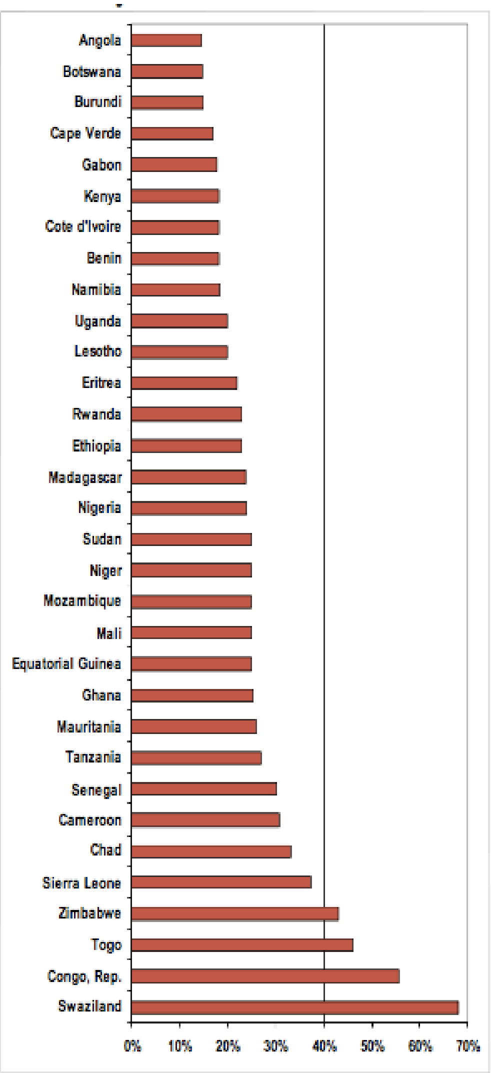
[3] One can use aerial bunched cables that are insulated to reduce tampering. Another approach is to have smaller transformers much closer to loads.

relevance of Smart Grids and what that means in the Indian context. In this paper we talk about low-cost smart meters which are one of the elements of a smart grid. A smart meter in the view takes here which is LIC context specific would be a meter that can at the minimum have three functionalities: i) convey consumption information to a central location periodically, say once every few minutes and ii) allow the customer consumption to be either "curtailed" or be turned off upon command from the central location. An additional feature of some of the low-cost smart meters is the ability to accept prepayment information and keep track of the customer credit. These can be implemented in various flavors and the term low-cost refers to a rough cost estimate of below $50 per customer. We return to a discussion of how these can be an early enabler of reducing losses and in the longer term could be a key instrument of the smart grid.

Figure 1 Total transmission and distribution losses as percentage of electricity sent to consumers. Data for latest year available 1999-2006. (From Monitoring Performance of Electric Utilities: Indicators and Benchmarking in Sub-Saharan Africa World Bank report 2009).



End-use Efficiency

The end-use of electricity is to provide the consumer with a service, for example the service could be lighting, cooking, talking on a phone, keep food cool or plants watered. Lighting has seen phenomenal changes in efficiency with the advent of LEDs. While lumens alone do not capture that (directionality of LED matters as well), we have seen in the last two decades a near seven-fold improvement from 10 lumens/Watt for incandescent bulbs, to 35 lumens/Watt for Compact Fluorescent Lamps (CFLs) to 70 Lumens/Watt and rising for Light Emitting Diodes (LEDs) lamps (Mubarak and Kashem, 2016). While for the rich, a lower cost light might mean more light for the same spending, for the poor it might mean the ability to afford light sooner. Lighting and electronics might be special cases, where the conversion from electricity to a service can be dramatically improved. Cooking with biomass on a three-stone fire might have an efficiency of 10 to 20% (energy into the pot compared to what could be recovered from the biomass if all of it fully burnt), whereas electricity used for cooking with an efficient device such as an insulated rice cooker could be multiple times that. An efficient pump combined with lower water requirements using say drip irrigation could reduce the energy for irrigation by half.

While end-use efficiency is not the subject of this paper, it is worth noting that some threshold effects can occur with extremely efficient devices or components working together. For example the efficiency of LED lamps and microprocessors have in turn lower the amount and weight of battery storage and PV generation required allowing the arrival of more efficient off-grid lighting products over the last five years. More importantly to this paper, such efficiency improvements are allowing new business models for energy access since an entrepreneur can exploit a chain of multiplicative benefits to bring the price points of specific services down to something affordable.

Losses in Generation Systems

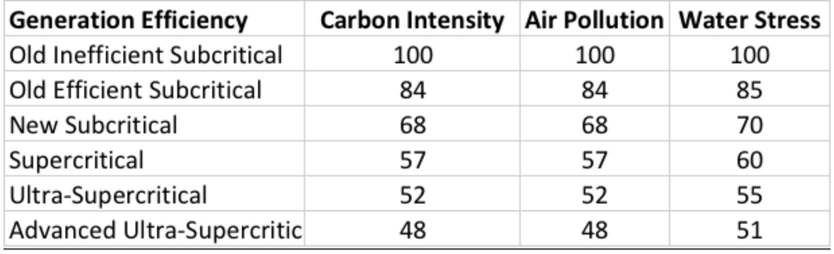
This discussion will address what the author sees as salient drivers and not try to be exhaustive with every technology.

Coal

In the below figure from a 2015 report on Stranded Assets and Subcritical Coal by Caldecott et al (2015), it is clear that generation efficiencies vary widely with coal-fired generation technology that is adopted. Moreover, in hotter climates, there would be a 1% to 2% reduction in efficiency due to higher ambient temperatures. So for example the recent Government of India decision to retire some older subcritical power plants creates the possibility of enhanced generation efficiency if under a separate decision making processes, the Government also builds new supercritical and ultra-supercritical units. Note that generally the decision to retire can be even more favorable economically and environmentally, as older units may already be in need of other refurbishment expenses, may also be subjected to higher water requirements, and given their history may be located in areas close to urban load centers where water stresses may be acute.

Aside from efficiency alone, the consideration of the health of coal miners, land restoration after mining, coal transport (e.g. port, rail) to plant, and local non-CO2 smoke-stack pollutants/particulates and the need for cooling water are becoming important considerations when considering the construction and operation of new coal plants.

Figure 2 Coal-fired Environmental Effects by Generation Efficiency, Base Level=100, from Caldecott et al (2015).



Generation Efficiency	Carbon Intensity	Air Pollution	Water Stress
Old Inefficient Subcritical	100	100	100
Old Efficient Subcritical	84	84	85
New Subcritical	68	68	70
Supercritical	57	57	60
Ultra-Supercritical	52	52	55
Advanced Ultra-Supercritic	48	48	51

Natural Gas

Natural gas happens to be one of the most versatile fossil fuels. In power generation, it can be used for large central power stations, using a combination of aero-derivative gas turbines with high enough exhaust temperatures that are capable of driving a steam turbine as well. These combined cycle plants can reach thermal efficiencies of 60%, especially in cold climates. Single-cycle operations with this fuel can be just as efficient as supercritical coal reaching efficiencies of 38% to 44%, with no large cooling water requirement, start times of 30 minutes or less, CO2 emissions that are in the 400 to 600 grams/kWh range with the lower figures representative of combined cycle operation and the higher figure for single cycle operation with low capex. Hence CO2 emissions in power generation can be nearly half of those from coal while non-CO2 emissions are also a large improvement over those from coal or diesel. Natural gas power generation is more scale neutral than coal, in the sense that smaller power (say 10 MW) plants do not pay as large a penalty in CAPEX and OPEX (primarily through loss of efficiency) as compared to say 100's of MW power generation units.

Natural gas is a heating fuel of choice in cold climates, an excellent cooking fuel, feedstock for fertilizer and many industrial processes. With gas pipeline infrastructure for bulk movement, long-term contractual and political stability allowed point to point movements at low additional costs for movement and intermediate storage gas.

In the last decades it also became possible to transport gas in liquid form as Liquefied Natural Gas or LNG. However, the massive supplier-side investments for liquefaction, a significant energy penalty in compression and cooling needed to liquefy, and then specialized means to store and transport in purpose-built tankers- meant an added cost to gas. Liquefied Natural Gas (LNG) is now increasingly becoming prevalent allowing trade and new entrants on the demand side that can import the fuel to a port using a relatively modest investment. Not needing longer-term contracts, entry to use became easier even though it meant exposure to volatility of spot markets. With LNG trade, countries such as Japan and India that are not self-sufficient in domestic gas, and now others (where demand is not met through domestic gas resources or where pipeline imports are not available) are starting to use natural gas as well. More recently shale-gas from United States also added to global supply as fracking led by the entrepreneurial and innovative culture of the numerous small well drilling companies in the US took hold. While this spread has yet to occur elsewhere at the same pace it occurred in the US, the supply boom in the US has kept gas prices low in the US, and have also depressed worldwide gas and oil prices.

Compressed natural gas (CNG) has seen some success especially in urban bus fleets since CNG tanks could be carried on a bus and also dramatically reduce particulate emissions in a city. In urban settings this has been particularly cost-effective when CNG for transport, combined with piped natural gas is deployed to create a large shift away from diesel and from LPG (to free LPG for other more rural markets where piped gas is not viable). Low supply costs once infrastructure is in place, could allow lower-income groups to shift away from solid biomass or higher cost LPG. Ancillary benefits also occur to industry, brick-firing, commercial food preparation and food processing industry due to availability of lower cost natural gas. An important research question is to determine what is the broader impact of such a transition for urban settings on productive use, industry, transport, and clean cooking. There are some anticipated innovations in carbon fiber tanks replacing steel tanks that would allow CNG at nearly twice the pressures and with lower tank weight, thus reducing the overhead of modular CNG movement.

Low gas prices have been both a boon and a curse for CO2 emissions since the fuel does provide 25% to 50% reductions compared to coal (or fuel oil or diesel) and yet cannot achieve deep (e.g. 80%) reductions in CO2 emissions. The boon is that in a world where consumption is still growing, natural gas can be an intermediate step towards emissions reductions. The curse is that it would reduce emission to an intermediate level but potentially slow down innovation and scaled deployments of renewables towards the goal of deep decarbonization. There are also studies (Brandt, 2014) that suggest that even small life-cycle leakages (of a few percentage points) of natural gas in the entire system could make emissions from gas approach coal emission levels, thus negating the GHG emission advantage of natural gas.

Many countries may find themselves in a position where given the recent depressed LNG prices, gas-based generation starts to look attractive especially when one considers the availability of international finance (unlike that for coal), and the high efficiencies of combined cycle power plants. But one must not ignore the roughly 10% loss of energy (majority of it in liquefaction) in the entire chain involved in going through the LNG route. Large amounts of capital are also needed in the entire liquefaction, storage, transport, storage, and regasification infrastructure, potentially tripling or quadrupling the cost of source natural gas from $1.50 to $2.00/MMBTU to $6/MMBTU. Subsequent pipeline transfer and distribution costs remain as with our piped systems, further adding $3 to $4/MMBTU, with city gate prices reaching $10/MMBTU (Demierre, 2015).

Nuclear

Nuclear power continues to hold promise to become a carbon-neutral dispatch-able source of power. Yet as Deutch and Moniz (2006) summarized succinctly “Key impediments to new nuclear construction are high capital costs and the uncertainty surrounding nuclear waste management. In addition, global expansion of nuclear power has raised concerns that nuclear weapons ambitions in certain countries may inadvertently be advanced.” Financing large costs of construction, $5 to $6 Billion for a 1000 MW power plant, long and uncertain lead times from project conception to commissioning, and have local skills for operation and maintenance have all made nuclear out of reach for most low-income countries. There are indeed additional concerns with proliferation. Thermal to electric efficiencies are not the primary concern in nuclear power generation given the low cost of fuel (relative to fossil fuels) and low GHG emissions. The promise of small modular nuclear reactors where power plants are of the size of 50 MW to 100 MW, where the core components can be factory made and shipped, and where issues of nuclear are addressed have yet to become economically and technologically viable. Even at $5000/kW they could provide an immediate commercialization pathway in developing countries for clean baseload power at $100 to $150/MWh, since nuclear power is a source of firm power. Note that generation efficiency is not a matter of debate but the storage and disposal of waste is.

Certainly, some nuclear power generating plants that need additional investments or renewed licenses are under economic pressure from natural gas in the US. They may also face pressure from variable generation which under some incentive structures can participate in electricity markets at zero marginal cost and can lower baseload power plant operator revenues. If nuclear is replaced with gas-fired generation, we would be going in the wrong directions when it comes to carbon emissions. In the short run gas may also see increased use since capex costs for simple cycle plants are low and these plants could see higher utilization due to their role in managing variability from wind and solar.

Variable Renewable Power: Wind, Solar

We have discussed conversion efficiency and capacity factors earlier. An efficiency issue with these sources of power however is the distance from generation to load. Resistive and Corona losses in transmission can range between 5% and 8% per 1000 km distance for high voltage (e.g. 765 kV) AC lines. However, if, say, power has to be moved much further the losses can start to add up. Moreover, if transmission lines are built exclusively to carry variable sources then any capacity factor for the variable generation also applies to transmission. This can mean that lines built exclusively for carrying variable source can cost 2 to 3 times as much per kWh compared to lines with load factors of 50%.

With increasing share of variable renewables, conventional measures of thermal efficiency, as were used in coal/gas/oil fired generation are not the relevant measures. The issue of capacity factor, primarily dictated by the nature of the resource to some extent the technology was already discussed. However, a measure that becomes akin to inefficiency is curtailment where either due to a variety of issues the grid in unable to absorb the power generated and the variable generation must be curtailed. The set of issues leading to curtailment might be diverse: faults in the immediate grid in vicinity of the wind/solar farm, requirements for frequency control measures, management of up/down ramps, reactive power, lack of ability on the utility side to measure/communicate/control, or optimal management of the fleet of generators to ensure stability/reserves, or simply due to the nature of demand. What is important to note is that some of the measures to reduce transmission/distribution losses as well as measures to reduce commercial losses will actually have co-benefits on this front. Quantifying those benefits in terms of financial costs and benefits remains important.

Choices in Generation

Until recently choices in generation systems in LIC settings were primarily determined based on a) availability of hydropower, b) availability or import of coal or gas c) nuclear or geothermal power in rare instances and d) heavy fuel oil or diesel power. All of the above are firm sources of power, and decisions were made by combining the economics of upfront capital cost needed, cost of money and recurrent costs. Cost reductions during the last two decades are now reaching the point where several countries are installing variable generation sources in scale.

There are geographically specific settings where indeed hydropower makes more sense and some of these settings have a vast potential resource. Inga Falls in the Democratic Republic of the Congo is one such case[4]. While developing any large resource where the local demand does not bring in investment, one of the key issues is how to evacuate the power, building new (or upgrading existing) transmission lines to areas where such power has a bankable market, and making the company managing and operating the power lines credit-worthy.

Coal vs Natural Gas (piped & LNG)

In the United States, replacing an old inefficient coal plant with a combined cycle natural gas plant can have a small immediate recurrent fuel cost implication. For example, when one replaces a 28% thermal efficiency coal plant burning $50/ton coal with a 55% CCGT plant burning natural gas at $4/MMBtu, the actual fuel costs are quite close, $26/MWh for coal vs 36 USD/MWh for gas-fired CCGT. Carbon emissions on the other hand would be significantly reduced from say 1.0 ton/MWh to 0.4 ton/MWh, with an implied cost of CO2 emissions to be roughly $16/ton. The arithmetic however, looks very different to a low-income country that does not have low-cost domestic gas or large shale gas prospects (at least at this point in time) and hence must import LNG at $7 to $10/MMBtu contracts. (Note that these are lower than prices just a few years ago, and in same vein not clear what they will be a decade from now). In this case, the fuel cost alone with efficient CCGT is about $80/MWh, as opposed to $26/MWh, a very significant difference. This is to illustrate that the shale gas boom in the US and its ability to meet emissions goals is very different from that of a country that does not have a low-cost domestic gas supply for its piped gas network.

On the other hand, building a new efficient modern coal power plant could reduce emissions by 40% and the high capital cost of a modern coal plant would be partially offset by fuel savings. Hence the cost of mitigating 40% of the emissions from an older coal power plant may be economically viable for a different setting from the United States. There are of course location specific issues such a country would face such as finding appropriate land/water and transport links if the plant is at a new location. In Sub-Saharan Africa if financing must come from multilateral banks that might be a barrier or alternatively the cost of capital might be high. From a global climate change perspective, the issue of replacing an old coal plant even with a much more efficient coal-fired plant would be

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[4] See for example the World Banks review feature story of this project http://www.worldbank.org/en/news/feature/2014/03/20/transformational-hydropower-development-project-paves-the-way-for-9-million-people-in-the-democratic-republic-of-congo-to-gain-access-to-electricity

seen as a terribly wrong move since the newer plant would likely remain in place for decades. There are externalities to coal which have not been accounted here, either in health impacts to coal mining workers, direct environmental impacts in areas of coal production and further potentially much larger impacts on health from non-CO2 emissions resulting from the burning of coal. Coal quality also varies geographically, for example Indian coal has lower calorific value and higher Ash content.

Can Countries Install Solar PV or Wind Instead of New Natural Gas (piped and/or LNG) or Coal?

Hydropower and geothermal power are highly location dependent. Nuclear is out of reach for most poorer countries. New coal and gas power plants might lock in carbon emissions for decades. CCS is not yet commercially and technologically ready. So many LIC are facing a quandary and the choices are limited. They will inevitably exploit coal especially if these supplies are domestic and imply energy security. In countries with domestic coal or domestic gas resources, fuel costs per MWh can be below $30 and for firm dispatch-able power these would appear very attractive.

Technologically today a kWh can be generated using solar photovoltaics (PV) at prices of 75 USD/MWh in low-income settings of Sub-Saharan Africa[5]. In many parts of the world where cost of capital is much lower, where could-free climates prevail and cost of labor is moderate (e.g. in the Middle East), power purchase agreements have been signed at nearly prices that are half of these. These are approximate figures since these supply costs vary with cost of capital, solar resource quality and how far one would need to string wire to connect the resource to the grid. However, many countries face additional uncertainties in deploying large-scale solar since the entire grid infrastructure system is not yet ready to receive large fractions of variable generation and hence the actual costs of integration and associated learning over time need to be estimated. Yet, if the time it takes to build large-scale infrastructure for feed-stock supply and large power-plants is a decade, there is a large question as to whether global assistance could allow for accelerated deployment of lower-cost renewables and technologies for integration.

LIC countries are also making moves towards larger-scale wind or solar where these variable resources are a small fraction of the overall generation mix. A somewhat special case is that of countries where the existing generation is primarily from diesel or heavy fuel oil. The high-cost of generation combined with a fleet of liquid-fuel fired generators, make it both cost-effective and technologically feasible to handle larger penetrations of solar and wind resources. Indeed, one sees Small Island Developing States (SIDS) to be in the front line of shift to large fractions of renewables in their energy mix.

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[5] Actual power purchase agreements in Sub-Saharan Africa have sometimes been even at higher price levels due to cost of capital and technical/financial and/or currency risks.

Hence there are many trade-offs a country might have to make in deciding the generation mix for the future. How to help address these choices in a way that makes choices and their implications transparent would be important. Summarizing some of the choices:

1. Exploit lower capital cost generation for the time being and wait until some maturity and cost reductions in renewable grid integration have occurred in the developed world. This would imply building a hydrocarbon based power plant if immediate acute needs for firm power exists.
2. Anticipate a technology such as carbon capture and sequestration (CCS) and if indeed coal power/gas plants are built, make them CCS ready for now with some assistance to make the additional costs worthwhile. However given how CCS is from readiness and uncertain cost projections, it is not at all clear where a LIC would invest in such an approach.
3. Richer nations of the world find it attractive to provide development assistance specifically for deploying low emission technologies where a larger fraction of variable generation is made viable on the grid through innovative smart grid measures. These measures may have a cost but they are least-cost in a global sense since they may be more expensive to deploy in settings with legacy infrastructure and high soft costs of deploying infrastructure.
4. Consider large scale deployment of rooftop solar especially where such deployments can replace some generation from liquid fuels and potentially lead to lower peak capacity requirements. Note that in low-income settings, the cost differentials between rooftop systems and large PV plants is lower. Moreover, rooftop systems might be supplemented with battery storage in LIC settings where immediate reliability improvements are unlikely.
5. A large focus on efficient appliances and the entire value chain of generation, transmission and distribution.

How to Unlock Investments for Efficiency, Access, Growth and Integration of Renewables?

The question of investments and financing can be very country-specific for two reasons. One is the financial health of the utilities, particularly the distribution companies and second the macro environment for borrowing the country might be facing. Having said this, the key question that most country planners have on their agenda is how to prioritize investments, and make the kind of investments that will lead to economic growth. So, if nearly all of the electricity demand is purely residential, then one can imagine that the overall impact on income growth may be low[6]. More crucially, such demand could have been met perhaps in the interim by much lower cost off-grid systems. On the other hand, if clear agricultural, industrial or services sector policies are identified,

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[6] Here one needs to note that when electricity tariffs are below some threshold (say about 3 cents/kWh), cooking with electricity starts to be an attractive option when compared to purchased or difficult to gather biomass. Associated impacts due to saving in time, lower environmental degradation and lower exposure to particulates may add up to significant benefits to the economy. Issues around such externalities have been difficult to research and quantify, however.

they would imply certain kind of investments to be more appropriate. For example, for irrigation, round the clock power may not be needed and allows for solar systems without storage to be readily deployed. Services sector might have large negative impacts from disruptions and hence might care about reliability while might tolerate a premium in energy charges. Industry on the other hand might require both low-cost and reliable power- and hence might be better located in special economic zones to start with. While all this might appeal to the planner, it might very well be that ensured reliable cost-competitive supply to nearly everyone in the country is a better approach, since that is least-cost in the long term anyway and such an approach lets productive opportunities emerge by creating an environment conducive to any sector or industry at any scale of adoption. So this is also a research question of linkages between economic growth and electricity access and reliability. Note that attributing lack of growth to electricity alone is difficult since one may also need to ensure good transport infrastructure, and low-transaction cost access to markets and good overall environment for business.

In our own work in deploying 16 mini-grids operating for 5 years, within a couple of years, it was possible to observe where there was significant growth in consumption and that growth could have enabled a dynamic signaling of where further investments are needed. This issue is worthy of further examination.

While the above comments are broadly applicable to any setting where access and growth investments are needed, health of the utility sector also determines the prioritization and sequencing of investments.

Countries where the electricity distribution utility sector is financially healthy

The utilities in these settings are able to make investments for maintenance and growth of distribution infrastructure while meeting its power purchase (or internal cost of generation) obligations. LIC countries are actually in an excellent position to make parallel investments in smart-metered distribution systems as they are the ones experiencing growth in consumption. Building in the absence of legacy systems would be more cost-effective. A financially health utility would have the fiscal room to also allow for investments in new connections and have the ability to wait out the firming of demand.

Countries where the electricity distribution utility sector is NOT financially healthy

In a recent study by the World Bank (2016), the report found that of a sample of 17 countries in Sub-Saharan Africa, only four had a healthy electricity utility sector in 2013. Many of the countries, especially those LICs where electricity access is not yet pervasive and where supply is still erratic need to grow generation, transmission and distribution all at the same time, while distribution companies do not even recover the aggregate recurrent costs from the tariff revenues. For example, the electricity distribution sector in India (largely parastatals) has accumulated losses of $60 Billion USD over the years. Incidentally the bulk of the losses in a handful of states of India. While the challenges of those utilities that carry the bulk of these losses in India are particularly large and unique, they nevertheless demonstrate how incredibly difficult it is to steer the system towards reliable and financially sustainable operation with such accumulated losses.

In such situations, it is conjectured here that the highest priority initial action would be BOTH technical loss reductions and bringing down commercial losses. One would expect a strong commitment from country leadership, the relevant power ministry and the utility. Our hypothesis here is that such commitment combined with new prepayment or pay-as-you-go technologies could be potentially be effective in addressing several issues at once. And indeed these multiple issues are intertwined. Pay-as-you-go systems can be deployed through the use of smart-meters. These smart meters would have to be low-cost meters that monitor customer credit and consumption in real-time as opposed to the monthly (generally manual) reading of a conventional electricity meter. Such smart meters would permit:

1. **Technical System Audit:** Combined with proper coding of assets (feeders, transformers) and customers would make it possible to carry out quantitative audits of the distribution system as a routine aggregation matter through appropriate software. In turn this would make it easier to identify which parts of the distribution are responsible for the highest technical losses (NRECA, 2015).
2. **Commercial Loss Reduction:** Smart metering could begin first with those feeders where there is higher demand density. In these feeders, ALL customers would be smart metered so that one could assess commercial losses fully and begin the process of identifying and addressing the underlying causes of the losses.
3. **Reducing Transaction Costs:** Meter reading and associated bill generation, bill delivery and revenue collection for small rural customers can have high transaction costs, especially in dispersed rural settings, and hence lead to inefficient staff utilization at the same time. In such settings the utility cost of collecting revenue could be substantially reduced through digital or mobile money.
4. **Building up Utility Technical and Commercial Data:** Increasingly the credit worthiness of the utility is determined to what extent it is backed by actual numbers. Even if the above processes are in place and the utility can demonstrate the cost benefits of such a program, additional financing for a roll-out of this program can be untapped from such programs. There are certainly obvious possibilities of output based aid programs, which ultimately can then lead to a larger demonstration of utility credit worthiness.

The other attractive aspect of this proposition (to be verified) is that the initial hardware investment is primarily in metering, communication, prepayment architecture and associated software. Note that prepayment architectures (e.g. in India where a national payment system is being envisioned) that allow not just electricity payments but other service-delivery payments complement such efforts. Such investment is likely to be modest compared to all the infrastructural deficiencies of the generation, transmission and distribution system and yet allow the initial step that could allow financing to flow for the entire system. The key outcome one is looking for identifying investments that make the most judicious use of capital in a way and also shows the pathway to a financially healthier utility and thus set in motion a virtuous cycle of greater investments that begin to address what might be accumulated deficits in aging or inadequate utility infrastructure.

Note that a utility that has technical losses of 25%, commercial losses of 30% and perhaps could be saving 5% of its current revenue that is otherwise spent on bill collection is only recovering 50% of the overall potential revenue. It is indeed possible to reduce technical losses from 25% to 16% and commercial losses from 28% to 16% as Rwanda did through the World Bank Rwanda Urgent Electricity Rehabilitation Project (World Bank, 2012). This project alleviated power shortages and enhances the capacity of energy sector institutions. The application of a prepayment system also cut commercial losses. The government significantly raised the power tariffs in two stages, and payment collection increased from 72 percent to 84 percent.

As being tried by the UDAY program in India, one could also imagine institutionalizing such changes in a rolling fashion so that places where such changes are made are also those that are prioritized for additional investments, receive power supply reliability first, and have the opportunity to write-off old debt to incentivize the utility.

The above discussion addresses the catalyst for larger change but changes would not be limited to just smart metering. Prioritizing, planning and the design/execution of other technical investments would be also important but would be prioritized as the next challenge. Here a major question looms many governments.

What to do in the interim?

While grid electrification plans (as well as financing or execution) are forthcoming, there is a more immediate need to provide increased and ideally universal access to electricity. One does sense a degree of urgency that is faced by the political leaders in their own countries to provide electricity access as well as improve reliability. To some degree this might be emerging out of the entire mobile telephony and smartphone revolution that has made inroads into places without electricity. Regardless given the imperative and the time-scales of actual grid implementation, which could take a decade or more, there is strong interest emerging in off-grid and grid-like mini-grid systems. The main advantage of these systems is their ability to bypass large centralized generation and transmission. The degree of access or service standard (primarily what appliances can one operate, and what flexibility for growth) or in recent World Bank led framework “tier of access”, is under consideration and consensus has not yet emerged around what level or tier would be an acceptable to which fraction of the population.

For example, the IEA estimates that about 40% of the world’s unelectrified population can be supplied with electricity at lower cost through the creation of mini-grids rather than by the extension of the main grid (IEA, 2011). While minigrids can be deployed rapidly compared to grid, they are not always lower cost than grid extensions for such a large fraction of the population.

Due to the simplicity of the business models surrounding a product sale, off-grid solutions such as solar home systems are taking off rapidly in the marketplace. They are now available from small systems with as low as 10 Watts of solar PV capacity to as large as 400 Watts. Some of the advantages of solar home systems are:

1. A direct sale to the consumer of a product that does not require any physical common infrastructure such as metering, wire and/or poles.
2. With decreasing costs of solar PV and storage one can afford to oversize solar and storage capacity, allowing for some degree of growth in consumption. So, individual systems get more attractive compared to minigrids with decreasing generation and storage costs.
3. Newer financing models leverage pay as you go features. The scalability of this proposition while keeping costs of collection and servicing low in rural settings is still up in the air, but perhaps with extreme reliability and increasing use of cashless transactions/banking this issue can be addressed.

What mini-grid solutions can do at lower cost than grid is to provide 24-7 access at a level of few kWh per month as opposed to hundreds of kWh a month that is common with a grid connection. Minigrids would certainly provide a much higher service standard than a solar home system. Minigrids are a form of decentralized electrification with a service-based approach, where a customer generally does not own the asset but pays a tariff or monthly fee for use. They can be owned and operated by nongovernmental entities such as cooperatives, community user groups, or private entrepreneurs, as well as public or private national utilities. Minigrids themselves are not new but the last five years have seen renewed interest due to the following developments:

1. Urgency of delivering visible benefits of public spending on electrification. Here mini-grids offer the possibility of offering rapid electricity access as one does not rely on long lead times associated with generation and transmission build-out.
2. Rapid decline in Solar PV costs. There has also been some associated decline in balance of system cost.
3. Penetration of mobile technology and widespread adoption of low-cost phones, increasing availability of wireless data coverage have led to innovations in payment systems. These innovations can allow capital costs to be spread out across time and/or implement pay-as-you-go models reducing transaction costs in tariff collection.
4. Development of supply chains with growing popularity of solar home systems. Decreasing costs of generation, efficient appliances and low transaction cost metering allowing operators to overcome some of the cost limitations of battery storage. This naturally permits closer to 24-7 service.
5. With a combination of solar PV, batteries, LED lighting and efficient appliances, it became possible to provide limited but reliable power without the high recurrent costs associated with fuel-based generation and the associated maintenance. In combination with remote system management enabled through communication costs, it became possible to drive down the costs of managing multiple installations.

6. Through geospatial planning it became increasingly possible for national-scale planning processes to identify geographical areas where minigrids would be an appropriate technology.
7. Global political recognition and engagement around sustainable energy for all and now the SDGs (energy is SDG 7) has led to policy makers and the institutions advising the governments to think about interim approaches.

Taking advantages of above features however required minigrid operators to develop new business models and deploy skills that would combine multiple new elements such as: new types of generation sources, hybrid operation, battery management systems, smart metering, wireless communications, new payment models, and remote management. Increasing use of data, for planning, assessment, sizing and operation also became an important means to drive down costs. Moreover developments in "internet of things" are beginning to show up in the low-cost metering and payment marketplace, which could benefit from some standardization and cost advantages through manufacturing in volume.

Paper 6.3 in the same theme will address the issue of "low voltage design" covering such systems where no high voltage transmission and medium-voltage distribution are involved.

Frequently investment effectiveness is poor because the electrification is not carried out in a programmatic sector-wide fashion that would have allowed designs and standards to be appropriate and supply chains as well as deployment talent ramped up. In this regard the following actions are also worth considering.

1. Low-cost approaches: material-efficient designs for reticulation structures and wiring standards
2. Appliance efficiency promotion what would provide gains to improved "service" without corresponding hard investments
3. Establish geospatial data-bases within the utility that can begin to tie together (a) physical infrastructure such as feeders and transformers, (b) commercial department customer databases and (c) staffing and maintenance staff associations, so that one can set the stage for a modern utility operation

Some examples worth examining in greater detail

- Regional transmission lines: Reducing losses and also reducing the overall cost of energy through interconnects and electricity trade. Examples of HVDC transmission lines between Kenya and Ethiopia (Oguah et al, 2015). The claim is that this will allow 2 GW worth of trade through a roughly 1000 km HVDC line at the cost of nearly $1 Billion. HVDC may also present advantages (and may be essential when connecting disparate grids that are not synchronized) at long distances (above 500km) than HVAC lines of the same capacity because of reduced losses and reduced right of way[7] (Behravesh, 2012).

- Have privatized utilities introduced technological improvements such as SCADA and GIS systems, improved metering, and registration and maintenance techniques, in order to meet the service quality requirements and the loss reduction targets imposed by regulators (ESMAP 2015).
- In 2008, less than 4% of the global installed base of 1.5 billion electricity meters could be considered "smart". However, the smart meter market is exceptionally local, with different drivers, regulatory environments, favored technologies, standards, value and supply chains, and especially, market timing (Pike Research, 2012). For example, China has a high penetration of smart meters (~67%) due to a decade of robust GDP growth, local technology development and rapid industrialization. Can one learn from that experience?
- Smart meters in the higher income countries are more for demand side management, "time-of-use" billing and peak power tariffs and necessitate high reliability of two-way communication networks. Can one imagine a low cost, lean design for the LIC market?
- Can one be spatially opportunistic, exploiting low-cost local sources where available and finding ways to harness the enhanced economic improvements from geographic areas that are initially connected to generate resources that supplement future expansion? That "Electricity for all" campaigns around the globe often fall short of their targets is partly a failure of planning. Planning for distribution networks could be improved by gathering data on end-use demand and deploying geospatial tools. Most important of all, the entire planning process from generation to distribution must be better coordinated if access plans are to be successful (Chattopadhyay, 2014*)*.
- Insufficient information on existing and new customers (including off-grid demand) makes it impossible to estimate future demand. Decisions about grid extension and off-grid electrification are driven by policy targets, with only limited planning and analysis to guide the operation of the system (World Bank 2014), the selection of transmission and distribution components, and the optimization of grid extension with off-grid solutions.
- Off-grid systems being currently considered could be made compatible with future arrival of the grid. So it is conceivable that a single phase 230V AC distribution mini-grid eventually become one leg of a larger 3-phase grid when the grid arrives. Can mini-grid deployments that receive public finance now, create an initial roll-out of prepaid smart meters ensuing learning as well as software development locally?
- Lack of adequate co-ordination might imply that a possibility of shortfall of supply of electricity might emerge. In the short term when supply proves inadequate, the utility usually ends up buying power at an exorbitant rate, and/or building small and expensive diesel-powered generation plants. The use of backup generators as a hedge against unreliable supply is estimated to cost African economies between 1 percent and 5 percent of GDP each year (IRENA, 2012). It is possible that a move towards a digitally metered approach could also allow one to schedule and curtail power and yet provide some minimum power.

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[7] A single HVDC line with two conductor bundles of same capacity has less environmental impact than a double circuit AC line with six conductor bundles.

- Which smart technologies can potentially be deployed in power systems and in what situations for better grid management and which of these technologies are adaptable to low income country situations? How can these technologies and innovative approaches promote the integration of renewables?
- Does one benefit from linking the need to build new infrastructure (schools, clinics, government offices, housing and roads) with electrical distribution?

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