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Low-voltage System Designs for Energy Access

Theme 6, Paper 6.3

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1 Abstract

The potential for innovative designs for last-mile distribution and/or stand-alone systems for electricity access in low income settings is explored. The last decade has seen innovations and scaling of off-grid technologies such as solar/battery home systems and minigrids. While still expensive per kWh compared to grid tariffs, they offer the possibility of a lower capex, faster execution times, and institutional flexibility particularly if planning for the first few kWhs/month of service. Their viability for immediate first access to lighting and small DC loads is becoming clear, but that of providing pathways to larger consumption and economic growth is less clear. The paper articulates research questions surrounding the emergence of demand, data based expansion of grid coverage, ensuring cost-effectiveness of resources, and pros/cons of time horizons in planning and addressing non-residential demands. What role do sectors-specific (e.g. residential, transport, agriculture, industry) needs and policies have on the prioritization of grid roll-out and minigrid deployments? The paper describes lessons learnt from several minigrids deployed in Africa and an example of agriculture-sector specific provision of electricity for irrigation. Some of the lessons from these innovations on smart metering and payments apply equally well to grid customers as well and the implications are discussed.

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2 Introduction

Last-mile access is discussed where we define low-voltage systems as any AC or DC voltage system for electricity supply that is below 600V. The voltage, AC or DC, stand-alone or minigrid of grid connected architecture, and maximum amperage level of consumer-side electricity service would depend upon the system design as well as operation. Technical choices such as system generation or storage capacity, peak power, energy limits if any, reliability of power, time of day pricing if any, payment plans, appliance choices and availability. From an economic growth perspective, how the services impact a non-residential user would be just as important. From the perspective of the service provider, whether a private entrepreneur or a utility, system design and associated policies/tariffs and regulatory framework would determine their profitability and ability to scale. From the perspective of the government it would be important to ensure public funds are well spent and lead to the objectives they want to meet. Since the cost, operational and business model choices can be quite different for different technologies and designs, it is important to think carefully about the options and implications.

Low-voltage systems can be part of a larger grid with central generation and transmission with a distribution transformer that connects to one or more customers. Low-voltage systems can also be mini-grids where generation, distribution and customer supply voltages are entirely at the same AC voltage, either 110V or 230V.

When it comes to all-DC systems, most systems are based on solar PV and batteries which are native DC technologies and solar home systems built around them try to use voltages from 6V to 48V. When distribution to multiple customers is present, higher voltages have been utilized or proposed. Systems that are entirely DC are not new to provision of basic residential electricity services and to the provision of lighting for vendors and shops. Being stand-alone individual systems, they can have the simplicity of appliance purchase (and multiple financing options) and are easy to install. Hence they bypass complex assessment, design, financing, procurement and installation steps associated with grid infrastructure. They also bypass the delays associated with generation, associated feedstock supply and transmission investments that must all occur at the same time. Hence there is considerable interest in these types of systems.

Until a couple of decades ago, low voltage systems, particularly 12V DC systems, remained the domain of boats, recreational vehicles (RVs), and those in the wealthier countries purposefully wishing to live off-grid. Living off-the-grid was possible if one was conscious of efficiency, conservation and willing to forgo developed-world conveniences of large electrical appliances. Using 12V DC made sense if one limited oneself to low-power appliances that in aggregate consumed no more than a few hundred Watts and clustered together in a small home or vehicle, the daily energy use was no more than a couple of kWh. Just two decades ago, high equipment costs for such a low-voltage DC system meant an upfront investment price point of several thousand dollars. No matter how creative the loan terms were, and how flexible the payment systems, this investment was generally out of reach for the poor.

On the other hand, grid access where available could be obtained for an initial cost on the customer side for a couple of hundred dollars[1] and a couple of kWh a day could be purchased in many countries for about $0.10 to $0.40[2]. For the poor (with say, a daily household income of no more than say $10) without grid electricity access, off-the-grid living was generally not a choice, and a consumption of even one kWh of electricity a day at a price point of grid tariffs (they could actually afford this level of expenditure) would be a dream come true. Hence from the consumer perspective this choice is frequently clear, provided impediments such as the high first cost of connections, long waiting periods or unreliable service do not intervene. Spreading the first cost to the consumer or making it country financed could easily address the first of these issues.

With the poor recognizing the enormous value of the first kWh in a month (let alone one kWh a day) with high luminous efficiency of LEDs and cell-phones, and the availability of dramatically lower cost solar PV combined with creative financing options (e.g. mobile money), have made adoption of small solar home systems and solar lanterns a real possibility. For this first monthly kWh of consumption, the poor were willing to place a huge premium (given that alternative such as kerosene/candle based lighting or paying someone to charge their phone are neither convenient not cost-effective if they could finance a purchase and trust the quality of the purchase). So when the solar lanterns and home systems reached a point when their initial cost could be recovered in a year or two, entrepreneurs took the opportunity and the market grew rapidly.

A brief overview of the technological choices available today is provided first. Here a distinction is made between direct current or DC (voltages as low as 3.6V[3]) and AC (alternating current) systems, associated efficiencies, along with distinctions between energy use and peak power capacity on the consumer side.

We start with stand-alone solar home systems and then move to the topic of mini-grids which historically were based on diesel generators, generally operated in evening hours (or as part of a fleet) to ensure cost-effective operation. More recently solar PV with batteries, or hybrid systems with an additional genset have become prevalent. These systems serve multiple customers and depending upon how they are operated, allow some economies of scale in maintenance, operation and asset utilization.

Implications of the dramatic reductions in cost of solar photovoltaics are discussed and if they continue to decline could create a disruptive phase that could lead to new designs and new paradigms for electrification. These cost reductions in solar PV and associated market volume are also lowering the cost of associated electronics, battery storage and small DC appliances.

[1] Different policies and distances from the grid could mean this upfront investment could be anywhere from $50 to $400 for many LICs.

[2] Note that grid tariffs vary both by country and level of consumption. So a grid tariff of $0.05 to $0.20 per kWh is representative of many LICs for the first few tens of kWh per month of consumption.

[3] mass-produced 18mm diameter and 65 mm Lithium Ion or LiPo cells (commercially sold as 18650 cells), have a nominal voltage of 3.6-3.7V. Note that this same cell is used in electric vehicles where several thousand of these are strung together today to reach storage capacities of tens of kWh.

Some of the developments in this space, particularly in the developed world settings are in a R&D phase, looking at either "emergency mode" operation of an islanded grid- sometimes called a microgrid that is temporarily cut-off from the main grid and would ideally continue to operate stably just with multiple local energy resources, control systems and smart management. We discuss these briefly but our primary focus is on the intersection of what is feasible in the near term for low-income settings, what are the likely features technically, economically and institutionally that are viable in the low-voltage space.

2.1 Energy Access

It is widely recognized that access to modern energy services is essential for economic and human development. Eberhard, et al. (2008, 2011) report that, to support the current economic growth and electrification plans in Africa, the power generation capacity should grow by more than 10% annually in the upcoming years. Foster & Briceno-Garmendia (2010) underline that the poor power infrastructure has significantly impeded growth in Africa and that, in some countries, poor electricity service is cited as the major obstacle for business. Deichmann, et al. (2011) cite a number of studies on access to modern energy services in developing countries. They highlight the positive impact of electricity access on health (lighting for clinics and refrigeration for vaccines), education and small businesses (in both cases, mainly due to the availability of electric lighting). Deichmann, et al. (2011) cite also Pasternak (2000) and Martínez & Ebenhack (2008) who show that, at the macro level, a strong correlation exists between energy consumption per capita and Human Development Index (HDI) (UNDP 2014). Alstone, Gershenson, & Kammen (2015) show that there is a roughly linear relationship between HDI and electricity access rate. Beside access to electricity, access to clean cooking fuels is another significant issue for sub-Saharan Africa (SSA). Today in SSA, most of the population relies on traditional biomass (mainly wood or charcoal) for cooking (IEA, 2014). Indoor air pollution produced when burning wood, dung or charcoal on open fire or in traditional stoves is responsible for a variety of health issues (WHO 2006). Additional issues related to the use of wood as cooking fuel are the significant amount of time dedicated, mainly by women and children, to the gathering work and the negative impact on environment due to the non-sustainable exploitation of wood resources in some areas.

There is the question of definition, as to when a person or a household can be considered to have access to electricity. Does a household that has the use of a single small LED bulb (at maximum, a few Watts) every evening from a small battery (charged by any means) have access to electricity? What about a person who owns a solar home system and in addition to lighting can charge a mobile phone or also watch television for few hours? What about a person who has a grid connection, but suffers from outages 40% of the time, especially when that disruption occurs just at the time they most need power? The World Bank has come up with the notion of tiered access to combine measures of service and power levels (which in turn translate into a capacity) and the duration of service. But many times, the issue of access is seen as static but our observations show that this is not the case. While difficult to provide, the poor associate electricity access with the ability to use *any desired amount* of electricity, available *when they want to use* it and pay for what they use not pay for a service that charges them a monthly fee and does not work 24-7. This is no different from nearly everyone's expectation from electrification or for that matter any service.

If one anticipated no growth in consumption and all the loads were known in advance, at low consumptions levels (of a few kWh per month, a consumption level that is commensurate closely with ability to pay), a stand-alone off-grid system will be a lowest cost system. Operational uncertainty, especially recovering the costs through small periodic payments remain and a considerable effort goes into developing models for efficient payment systems. A micro-grid shared amongst several customers can provide a higher quality service (larger peak loads) and flexibility to grow load and from a commercial operation standpoint, provide the benefits of aggregation.

3 Technical Background for Electricity Distribution

At the risk of some generalization, an overview of the issues in electrification is provided. Early electrification occurred through centralized power plants that allowed:

i) centralized operation and maintenance using skilled personnel of power plants which were essentially operated as if they were large industrial facilities.
ii) use of AC current that could be easily "transformed" to higher or lower voltages at generation facilities, sub-stations or at distribution transformers to keep wire costs manageable and
iii) servicing of customers large and small; as well as allowed customers to grow their consumption without making generation-equipment investments on their own side. In fact if any anything the cost per unit energy would go down. This both small loads (such as lighting) as well as substantial motor loads (whether for industry, commerce, cooling, appliances) were equally possible to power.
iv) an entire appliance industry to develop that utilized the AC power. Note that the electronics revolution based on DC came later.

The early sources of power (say up to mid 20th century) were either obtained by converting heat from fossil fuel combustion (coal, lignite, oil) or from geothermal sources. Direct conversion using hydropower was also utilized. The second half of 20th century saw the emergence of newer technologies such as nuclear power, natural gas-fired turbines and more recently wind turbines and solar photovoltaics. Electricity began to be recognized as a general purpose technology imperative for all to have access to and critical to provide the underlying necessary (but not sufficient) driver for economic and social development.

Today nearly 6 out or 7 people have access to grid electricity even though the supply is erratic for 1 out of those 6. This is not rooted in technological challenges but nevertheless is an important factor in decision making.

Even with the dominance of centralized power, there were communities that were too far/remote or too small, or were or small-islands. These communities developed their own low-voltage designs. Other developments such as lower cost solar also took place in the last two decades. These created the possibility of distributed power generation. The prime drivers that might enable small-scale decentralized power to play a larger role are listed below:

i. A fraction of those not connected lived in places that might be too remote or dispersed or in countries with low income so that those governments found it too expensive to connect them to the grid. There were solutions such as diesel fuel driven generation which were technologically somewhat easier to maintain and possible to scale down to relatively smaller loads, to hundreds of kW instead of hundreds of MW, but relied on expensive liquid fuel. Higher income countries found it justifiable to connect their own remote populations using such an approach. Lower and middle income countries plus small island states also took this approach, bearing significant cost disadvantages and creating impediments to their own competitiveness.
ii. Integrated Circuit (IC) electronics revolution (as a distinct development after the electricity revolution but relying on the electricity backbone) resulting in massive increase in the use of electronics, integrated circuits, mobile and wireless, internet-of-things for everything from communication, control, computing, entertainment, appliances and LED lighting which are primarily DC loads- occurring with the revolution in integrated circuit technology. It is now thought that ICT (information and communication technologies), enabled through IC today, is also emerging to be a general purpose technology. An important point to note about the electronics revolution of the last two decades is that it primarily relies on lower voltage DC electronics with power levels that are much lower than those for motor loads. So in comparison to electrical appliances such as older television sets, fans, small pumps, electric range/kettles, washing machines, refrigerators, air-conditioners (many of these were primarily motor or resistive loads) that added together could easily consume a few kWh a day[4], the newer electricity uses such as modern LCD TV, laptops, mobile phones, or LED lights are possibly a tenth of those loads. While in the developed world context one could argue that lower consuming technologies have simply led to lot more use such technologies, at least partially negating the efficiency benefits, in the poorer parts of the world, it has begun to enable some basic services (lighting, cell-phones, televisions) for the first time, made possible with much smaller electricity consumption. In the jargon used here, electronics enabled "high-value to cost electricity services", when compared to older generation electrical appliances and incandescent lighting allowed new low voltage designs. We will come to the issue of motor loads later.
iii. Electricity demand evolution characteristics may be different, as one tries to electrify communities where the populations might be distant from markets/manufacturing jobs, predominantly producing food for self-consumption or simply too poor to own any appliances beyond lighting or cell-phones. With a shift away from small industry and manufacturing in many countries or in the absence of lift irrigation or agro-

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[4] a toaster or a microwave might consume 1000 Watts of power over a few minutes of use, or a refrigerator might consume 100 Watts intermittently but adding to ten hours a day.

processing/storage demand, perhaps the electric loads are lower compared to say what happened in the development process elsewhere. Hence one needs to examine the fraction of commercial or motor loads that might evolve even with grid power available.

iv. Dramatically lower cost of solar photovoltaics (native DC source) which when combined with some electronics and batteries allowed self-contained systems whose costs scale with surface-area of the solar module (at least to first order) and hence allowing smaller generation levels without significant penalties of smaller scale. This smaller-scale stand-alone generation/storage possibility at corresponding smaller cost (compared to say a petrol or diesel generator) made it possible to provide high-service benefit to consumption.

The recent decline in solar PV costs have created another choice, whether solar PV generation should primarily be grid connected or not? It is important to clarify this issue in the next section along with associated jargon.

The above considerations illustrate that it is possible to explore new choices for unconnected consumers and hence at least for some of the populations, country policies could instead focus on connecting those to the grid where it makes most economic sense. It is also crucial to clearly identify the cost curves for electrification as one anticipates future roll-out of the grid. For example, a significant fraction of the unconnected population might actually be quite close to existing distribution wires.

A major research question illustrated in the paper is the need to clearly identify the cost-effective pathways that use scare public funds judiciously for provision of electricity services. An associated question is how to identify whether a proposed location is likely to have use for motor loads, electrically driven productive uses, small industry, air-conditioning or heating, refrigeration, pumping, cooking or electric-vehicles. Such demand forecasts would have significant implications on technology choice and on costs.

3.1 Solar PV Technologies: Off-grid or Grid-connected.

It is important to establish here the distinction between grid connected solar and off-grid solar. Grid connected solar can obtain power from the grid when the sun cannot provide for the demand and can feed surplus power into the grid when the consumer demand is lower than what can be produced with the sun's radiation. With such an arrangement, if the grid is reliable then your individual need for battery storage is eliminated, reducing both the capital and maintenance costs of the consumer. We set aside the issues faced by the grid operator, for the time being. Many believe that solar PV has reached "grid parity" since the costs of generation are comparable or lower than the cost of grid supply. This certainly not the case today for those who do not have the benefit of back-up grid supply.

The variable solar generation between sunrise and sunset, even on a cloudless day changes form weak sunshine at sunrise to peak sunshine at noon and then reducing again as the sun goes down and becomes zero at sunset. Even in the best of locations the entire day's cumulative sunshine (so to speak) might be equivalent to six hours of peak sun. With clouds and seasonal changes, the actual may vary from 2 to 6 hours equivalent of peak sun. Moreover, since the generation is zero after sunset when actually some of the electricity needs are largest there is a need for electricity storage in some form. Such storage and associated electronics would actually dominate the cost structure of an off-grid solar home systems today.

A 1 kWp solar module that might cost $1000 to install on the roof in low-income countries might generate anywhere from 2 to 6 kWh per day (with exceptions of course). If the daily generation is 4 kWh per day and one uses a fourth during the daytime, the cost of storing the other 3 units is nearly twice that of the solar module itself, thus tripling the total investment of $3000. With potential costs of financing, associated costs of managing the financing and maintaining systems, one could potentially expect an annualized cost of say $900. There are inefficiencies in generation (temperature effects, resistive losses), in battery storage and in power management (converting DC to AC for example) and increasingly inefficiencies on the load side as well. Consumer loads may also vary through the year and not necessarily match the variation is generation. Given all of these reasons, it is not unusual to be able to able to effectively use only 2.5 kWh/day or about 900 kWh per year. While being somewhat simplistic with the arithmetic, one can see the costs to the consumer for a kWh can be $1/kWh, much higher than grid tariffs.

An important research question is whether scaled-up manufacturing of systems, could drive down costs sufficiently so that an upgradable DC system that can grow with load, with absence of losses in going from DC to AC and back to DC for electronics dominated loads, with longer lasting batteries, with very efficient DC appliances, become viable. Perhaps one can get away with a system that is halved in peak generation capacity. Moreover, the system costs through mass manufacture and reduced costs (of say storage/PV/electronics and financing/management) be further halved per unit peak generation capacity. It is conceivable then that effectively one could have reduced the overall costs to a fourth of what they are today in the field. While there are many caveats here, the potential of such systems is not out of reach and raises research questions to examine this option as well. Nothing technically prevents these systems from becoming interconnected into minigrids and eventually feeding power into the grid when the grid arrives.

3.2 Current Off-grid Stand-alone Systems

Stand-alone off-grid systems that are specifically designed for an individual customer have seen rapid adoption even commercially without public grant funds or subsidies. They are nearly always some combination of photovoltaic modules and battery storage. These may be entirely DC systems with solar PV and battery storage both being native DC, and appliances that are DC as well. These systems can vary from something as small as essentially being a rechargeable flashlight with its own small solar panel, also called "solar lanterns", to systems popularly called "solar home systems" which are anywhere from tens to hundreds of Watts in peak capacity. In larger systems some anticipated use may be for AC appliances, and hence a DC to AC inverter is provided. None of these have any fuel-based generation backup. These have scaled rapidly with novel financing mechanisms several companies such as Dlight, M-Kopa, Mobisol, Azuri, Offgrid-electric providing service.

There are larger systems which can be from a kW scale to tens of kW scale for residential or commercial office needs. They may also have a petrol or diesel generator backup. In some windy locations the generation source could be a small wind turbine. These may either be in locations complete absence of a grid or maybe used by those wanting to ensure supply when the grid is down. While we attempt to be general, there has been near explosive growth in the solar lantern and the solar home system (SHS) market in the last five years. Hence we will limit our discussion to solar lanterns and the larger Wattage SHS. While a captive power plant of an industry can also be considered a stand-alone off-grid system, we will not consider that here.

3.3 Low-voltage Distribution (in grids and small grids) and Minigrids

Another category is that of a broad class where essentially the stand-alone systems described above are used as the generation system but now distribution wire provides the electricity to each customer. Here, both the generation and storage are shared by a group allowing customers to benefit from a larger shared power capacity than they would have had if they had bought their own individual systems with the same investment. There are also some management efficiencies for the operator, where for the customer there are some advantages in a service-delivery based model. For example, the consumer can vary their consumption as their ability to pay varies. Moreover, the utility need only supply what is paid for. Here the distribution system can be AC or DC. These minigrids or microgrids (sometimes even called nanogrids since there can as few as 30 customers) have the distinction that here, from a customer perspective the service could be grid-like with the customer simply paying for the use of electricity and not having the burden of maintenance.

There are numerous interpretations of the term "low voltage systems" in the context of electricity access in low income countries. With changing landscape, it is important that we list the broad possibilities first. Before narrowing the scope to a few, it is important to be aware of the broader discussion.

Here low-voltage systems are categorized as follows:

a) AC Distribution networks that are not grid-tied and are powered by local sources that could be either 110V/208V/240V AC or 230V/400V AC. Here there are no transformers utilized and the network range is no more than a km. Energy sources that are most prevalent are:
    i. Sources that are native AC power. Examples are liquid fuel powered gensets or occasionally biomass derived gas. In this scenario, the generator itself produced AC voltages and hence it was natural to distribute AC electricity to the customer premises. The author has observed even small 450 Watt petrol generators that

would be operated few hours in the evening and the electricity being shared with multiple households for electricity access.

ii. AC Distribution networks powered by DC sources such as solar PV/battery systems but then an inverter is used to distribute AC power to keep wire costs low and allow AC appliances to be used, while sacrificing some efficiency. Here the distribution is generally single phase AC at 230V.

b) Sometimes these low voltage AC distribution networks are connected to a medium-voltage line when there the source of power is anywhere from a km to at most few hundred kms. These systems are frequently seen when the loads are between 100 kW to tens of MW. We will call these small grids. Historically this has been the case when a geographic area (anywhere from multiple communities and/or small towns or an entire small island) is powered by one or more large co-located diesel genset(s) or a local hydropower resource. Increasingly wind turbines and solar PV are also utilized to reduce the fuel/operation of the genset, or to stretch hydropower reservoir operation. Given the distances and the loads in these networks, nothing higher than 33 kV medium-voltage lines are utilized. From a low-voltage distribution network perspective, these networks are not very different from those described earlier. From a historical perspective, these systems built around heavy fuel oil and diesel became particularly vulnerable to high fuel costs, further exacerbated by the high cost of delivery of fuel due to remoteness. However, with the recent decline in liquid fuel costs, heavy fuel oil (HFO) has traded as low as $400/ton and with large MW scale generators needing about 250 grams/kWh, the fuel costs per kWh can be 10 cents/kWh, which is comparable to bus-bar costs of other generation is many settings. However, one would then remain reliant on price fluctuations.

c) That part of the grid network that connects medium voltage (or MV) system wires (typically 6kV to 33 kV, which might in turn be fed by transmission lines from multiple centralized power plants), to customer premises through a system of transformers and wires. Note that these are simply traditional AC grids where a customer receives either AC electricity which is either 120/240V AC or 230V/400V AC, those being the dominant electricity distribution systems[5]. Here the transmission, MV distribution and LV distribution are all AC, so these are in effect an HVAC → MVAC → LVAC system, the most common grid configuration found around the world over. A novel and interesting paradigm is being considered by some where, these traditional AC grids would signal generation shortfall (could be a demand response measure to accommodate variable renewables), where the same distribution wiring inside customer premises would switch over to a locally powered DC source at 48V

[5] Note that in the US or Central America, the MV system (a 3-phase 4-wire system) supplies single-phase distribution networks that in turn energize numerous single-phase transformers, much closer to the loads. The secondary windings of these are center-tapped to produce 120/240 V single-phase 3-wire supply to the customer. In European countries the standard 3-phase 4-wire LV distribution voltage levels are higher, 230/400V and feed a low-voltage distribution network (generally to distances of less than 600 meters, but can be longer in remote areas) that serves multiple customers. See Figure in Appendix from http://www.electrical-installation.org/

or the AC supply would be transformed within customer premises or at a distribution transformer nearby to 48V and power essential DC loads only.

d) In the higher income settings, with increased interest in renewables and in resilient grid networks, there is an interest in systems with potentially multiple generation sources, some AC, some DC, including perhaps a main grid, and how these would operate in an "islanded" mode during potential grid disruption. These systems are also called microgrids in the literature. With one of more of distributed generators and/or wind turbines that are AC, and variable DC sources (e.g. Solar Photovoltaic) or firm DC sources such as a fuelcells, that might feed into a small grid, and potential use of storage, a plethora of different combinations and architectures are possible. The formal US DOE definition of a microgrid is "a group of interconnected loads and distributed energy resources (DER) with clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid [and can] connect and disconnect from the grid to enable it to operate in both grid-connected or island mode." The main challenge in controlling these systems is to ensure rapid seamless stable continued operation when the grid is disrupted. Some of these architectures have been deployed and separately addressed in other themes, and by the IEEE[6] and are still "research-grade" at this point in time. Here we will limit discussion to systems where two different generation sources are combined, one a AC petrol/diesel generator, and the other a variable DC source e.g. a PV array, along with battery storage. Inverters are commercially available today that can ensure either off-grid operation or grid-tied operation under this scenario.

e) It is very possible and indeed been discussed (author is not aware of installations though), where PV arrays feed a distribution system that is 380V/400V DC, since the DC to DC conversion would be more efficient and the equipment more compact. This 380V distribution would overcome the high wire costs of 12V-48V voltage DC architectures. Inside customer premises 380V would be converted to one or more lower voltage levels for DC appliances. Increasing use of DC end-use devices and appliances means that one avoids DC to AC and AC back to DC conversions. The combination of solar PV arrays wired at several hundred volts, and the higher 380V DC network would then be combined with some of the power distributed within the home at an even lower DC voltage (anywhere from 12V to 48V). Current thinking in this space is that both 380V DC (for higher current draw loads) and a lower 48V volt wiring for the smaller DC loads would be present. For safety and wire cost reasons sometimes the discussion is limited to 48V, also a standard in

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[6] An IEEE paper by Barnes et al (2007) summarizes numerous concepts and their implementations. Generally, the distributed generators by themselves are not fully controllable synchronous units, which are otherwise normally responsible for voltage and frequency control in conventional power systems. Therefore, power electronic interfaces (dc/ac or ac/dc/ac) are required in such microgrids (Lopes, 2006). Control, communication and optimal operation of such concepts are still being studied and they have been proposed as a solution to the conundrum of integrating diverse amounts of micro-generation without disrupting the operation of the utility network. These microgrids are anticipated to also provide ancillary services such as local voltage control and they could potentially disconnect and continue to operate autonomously. This operation has the potential to improve power quality to the consumer and shield the customer from grid disruption and vice versa.

telecommunication systems and automobile industry. Multiple 48V DC to lower DC voltage conversions would continue to be needed but these are likely to be low-cost and efficient at scale.

Significant system-wide changes would need to be implemented if countries (and the world) want to make a shift to a distribution system that is DC assuming the medium voltage network would still be AC. In a world where the several billion pre-existing customers and their existing AC-wired appliances are already in use, this shift would involve large new investments both on the public and the private side.

An unresolved question is whether low-income settings are the right place to start this transition. Given that infrastructure is still being built there, can they leapfrog ahead of legacy designs that will become antiquated soon. Alternately, the price of electricity storage could become low (mimicking the drop in solar PV prices), and/or very deep gains in appliance (or service) efficiencies that would make the very idea of a grid obsolete. In some countries, the coordinated growth requirements in generation (and associated fuel feedstock supply), transmission and distribution are so large that the process of grid electrification might take a couple of decades. Indeed, if this is the case should the individual off-grid systems and the mini-grid systems be all to some common DC standard, creating a large demand-side pull for DC appliance manufacture?

Early stages of any transition are inevitably expensive to carry out however. Even though they may be cheaper to carry out in the low-income settings when compared to high-income settings, this advantage is relative. Absolute costs of the transition may still be high compared to what they would be to stay with the conventional AC distribution standards as they are. Poor country leadership is also unlikely to be seen as taking on the burden of being the high cost first adopters, given that systems for international finance and delivery of aid are complex, time-consuming and prone to uncertainties.

It may be that at least some appliances with native DC circuitry might be offered for both AC and DC voltages. Meanwhile the drive towards larger renewable penetration and roof-top solar systems (or for that matter any customer side generation and storage equipment) will also enable innovations in hardware (e.g. edge of the grid devices and adjustable voltage transformers) that allow the AC grid to operate with DC sources.

The arguments for DC supply to the customer are further compounded by the fact that many income generating and small industrial activities require robust AC induction motors, for which the designs, manufacturing, and distribution/maintenance supply-chains are well developed. They would benefit in many settings from voltage and frequency stability of the AC grid, but these shortcomings have more to do with institutional issues and not with technology.

It is important to summarize here the broad choices that most customers have today.

Low-voltage connection to an otherwise AC grid

1. Connect to an AC 230V grid. Here depending upon the country you are in, the first costs could range from $50 to $500. This is the single largest impediment on the customer side.

There are impediments on the utility side as well and they are associated with issues already discussed in paper 6.2 under theme 6.

Off-grid connections:

2. A standalone system such as a solar lantern, a packaged device sold with a small solar panel, a battery and with one or more lights, generally LEDs and frequently DC ports for charging cell phones or operating some small DC appliances. At higher consumption levels there are solar home systems, costing anywhere from $100 to $1000 with typical solar panel Wattages ranging from 10-15 Watts to 100-300 Watts. They can either be purchased outright, or they can be financed in a variety of ways. Pay-as-you-go was a major enabler of growth in this space, allowing the customer to pay small amounts periodically, and the seller or service provider, either through technology or social means, ensuring that the customer does indeed make payments or otherwise the functionality of the entire system in disabled.
3. Minigrid connection where the minigrid either has storage or has a source of firm generation in the form of a petrol or diesel genset or both. Here the main advantages are that it can be a grid-like service with a service-based payment and shift of all capex and maintenance to the operator. The second advantage is that an individual customer can enjoy a much higher power capacity compared to the capacity of a stand-alone system. So a 10 kW or 10,000 Watt minigrid serving 100 customers does not just allow a 100 Watt peak load for each customer but potentially a much larger peak load since not all customers are likely to be consuming at peak level at the same time. The negative side is that it has all the risks of someone owning and operating a shared system, as well as additional investments in wire.
4. A fourth option is being considered by policy-makers as well. Frequently the utility for reasons outlined in a complementary paper, the utility parastatal does not have either the credit-worthiness or the institutional capacity to roll out low-voltage networks, and at the same time create new generation capacity and build new transmission lines. In this case, one could create the regulatory framework to allow the private sector to build large multi-MW minigrids (potentially powered by a fleet of gensets with or without daytime solar PV or wind) to grid reticulation standards and provide for the same level of customer service expectations as the grid. In this case the savings in capex might be small when compared to the grid, but access could be provided faster. It may also be that the generation shortfall in the country is so large that any additional generation, even fuel oil based in welcome. The thinking here is that these mini-grids are a planned precursor to the arrival of the grid, and that no major additional expenditures would be borne when the grid arrives. The main purpose of building minigrids in this case, is to provide grid-like access much earlier than when the grid arrives.

Given the varying upfront and recurrent cost structure of such options, and the different potential institutional arrangements that would be made with the private sector when one transitions from a minigrid to a grid, a major research question is to carefully examine the choices above. A valuable addition to the policy toolkit would be an effective articulation of a choice and transition away from that choice considering the financial, institutional and regulatory factors.

It is crucial to observe that the current price points, the recurrent costs per kWh can be anywhere from 3 to 6 times for the off-grid and mini-grid options when compared to the recurrent costs of a grid connection. The primary contributor of this high recurrent costs are i) the use of battery storage and/or ii) use of liquid fuels. There are exceptions, such as when a small hydro source of a local geothermal source powers a mini-grid. Not counting these exceptions, the inability for solar or wind alone to provide firm power, implies that recurrent and replacement costs associated with battery replacements or fuel are needed.

An illustrative example with nominal cost figures is instructive. Imagine, that the costs to the distribution company (extending a medium voltage line, low-voltage line, service drop, metering) per customer are $1000. The investment in generation and transmission is made whole through a tariff. If the electricity consumption over the next 10 years is 1000 kWh/year at 12c/kWh then the $120 per year in revenue goes to pay all the recurrent costs of the grid connection.

On the other hand an off-grid solar home system or a solar+battery minigrid that would provide 1000 kWh/year would be at least twice the initial cost of a grid connection. Recurrent costs would be significantly higher (nearly 50 cents/kWh) when one counts the cost of battery replacements and/or fuel. Utilities or private providers would have to quadruple the tariff to recover these costs.

There are two ways to circumvent this conundrum. Either design the off-grid systems or minigrid systems for a considerably lower load, say 200 kWh/year and hence reduce both the capital outlays and the recurrent costs. This is indeed a possibility and if private sector innovation and competition would allow the lower service standard minigrids to at least recover their recurrent costs and perhaps some of the capex as well. Through the use of digital metering and payment systems the transaction costs could be kept low. Over time one would build up consumption levels in the area, and a dynamic approach would be taken where based on observed speed of demand growth, grid access would be prioritized.

The high overall costs of off-grid and mini-grid systems does suggest that at the current state of technology and price points, grid access is frequently the lowest cost option. An unresolved question here is to how the utility or the relevant ministry can stage and sequence these processes to balance the needs for timely access while ensuring that costs are commensurate with the benefits. In particular, one needs to examine whether smaller solar home systems, that can provide services such as lighting, cell phone charging, television (broadly small appliance) are adequate to become engines of economic growth.

4 Some Past Data Points: Willingness to Pay for the First kWh/Month

Any design in order to estimate both financial and economic returns as well as establish the efficient need for public finance, must also consider that the consumer can afford and for what service. It often happens that the poorest pay the most for inadequate services, and the energy sector is no exception. Mills (2005) showed that people that use fuel for lighting (one in four globally) account for 17% of global energy costs, but only receive 0.1% of the lighting. Due to geographical, mobility, and financial constraints, most poor people in rural areas are forced to use locally available options that require little to no upfront investment and can be purchased in small quantities. This means that poor people often are forced to spend a large percentage of their income on energy because it is crucial that they have energy to cook and have some amount of light at night. This willingness to pay for a basic amount of energy is very important to note because it gives a minimum level of service that is considerably more valuable than subsequent energy used for less crucial needs National electrification efforts are important because they allow people to get much better quality lighting with the same or less amount of money. Figure 1 compares various options that are commonly used for lighting in developing countries, and the equivalent amount of energy used per month to give an idea of the scale of the disparity in lighting options. Key assumptions are outlined in Table 1. For non-electrical options, the equivalent kWh price was found by assuming an efficacy of 90 lumens/Watt because that is average for an LED. The actual lumen output of the non-electrical options was then used to find a power in Watts. An average use time for one unit (candle, liter of kerosene, etc.) was then used to find the amount of "energy" in one unit (in Wh). Mills (2005) did a similar analysis to find a cost per lumen-hour for similar technologies, and the basic conclusions were the same with candles and kerosene costing magnitudes more than electrically based options.

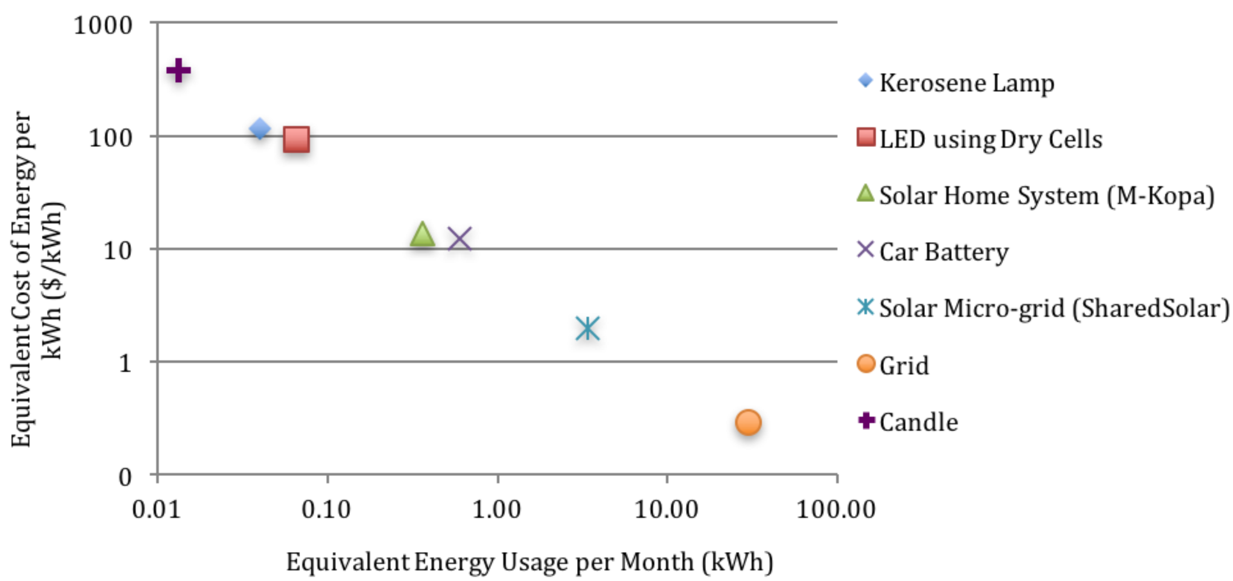


Figure 1: Equivalent cost of lighting for commonly available options in developing countries. See Table 1 for calculation assumptions. This figure is constructed from diverse data sources using assumptions shown below.

Table 1: Assumptions used for energy cost and usage estimates in Figure 1.

Lighting Source	Assumptions
Candle	2 candles used per day, 10 lumens average
Kerosene Lamp	10 ml/hr burn rate, used for 4 hours a day
LED using Dry Cells	Battery capacities, lumens and lumens/watt values were measured from small lanterns in 2012 and an average was taken, 4 hour daily usage assumed

Car Battery	12V/25Ah battery, 5W of LED lighting used for 4 hours per day.
SHSy (M-Kopa)	1W x 3 LED bulbs used for 4 hours per day, cost of system divided over 5 years
Solar Micro-grid	$60 connection fee, 2 to 20 kWh/month of flexible use with peak power capacity allocation of 500 Watts.
Grid	$120 connection fee, $0.25/kWh, assumed usage of 1kWh per day

In order to explore the commercial viability of grid-like access to provide flexible power (within limits) and to observe consumption growth, emergence of small business under reliable supply of electricity, 16 minigrids were deployed in Africa. Of these 8 in Uganda were carefully monitored for the first four years since June 2011. The deployment (called SharedSolar) provided near 24-7 reliable AC electricity supply, on a pay as you go basis. The tariffs charged were at cost recovery rates (if the entire installation and procurement had been at scale and not at the costs incurred in the pilot) and included time of day pricing. Upfront costs were wrapped into the tariff with a small payment of $50 for inside home wiring and wire to home. All systems were fully solar and battery systems with diesel genset backup. The systems were adequately oversized to allow for reliable supply for the first few years even with consumption growth which did in fact occur. Tariffs were progressively reduced as customer payments in effect were paying off the initial capital. This decreasing pricing also allowed for one to observe to some degree the effect of pricing on consumption but this was in no way a rigorous study in this regard.

Figure 2 shows the evolution of the electricity consumption over first three years, from the start of the operation, for the set of micro-grids in Uganda. It can be noted that despite the high price per kWh (from $3.2/kWh to $1.2/kWh in the day, and from $4.0/kWh to $2.0/kWh in the night), which is an order of magnitude higher than usual grid tariffs, there has been a very strong growth in electricity consumption. This demonstrates that people are willing to pay dearly for the electricity needed for modern electronic devices (LED lighting, cell phones, radio, small television sets) and even to some degree for refrigeration (amongst the wealthier customers and commercial users).[7]

While this not show the highest tariff that people were willing to pay, Figure 2 does provide a strong indication of what value households place on electricity. An important observation was that the consumption growth was not uniform across customers. We will look at this carefully below.

[7] It should be noted that this is on the scale of a micro-grid, and overall usage is much lower than the grid. The prices of electricity are also much higher for the micro-grid than a grid connection, and there is no guarantee that grid customers would react to pricing changes in the same way as these customers. It is reasonable to think that customers have an approximate amount of money that they spend on energy per month, and if they notice that their bill goes down, they might consider buying a new appliance.

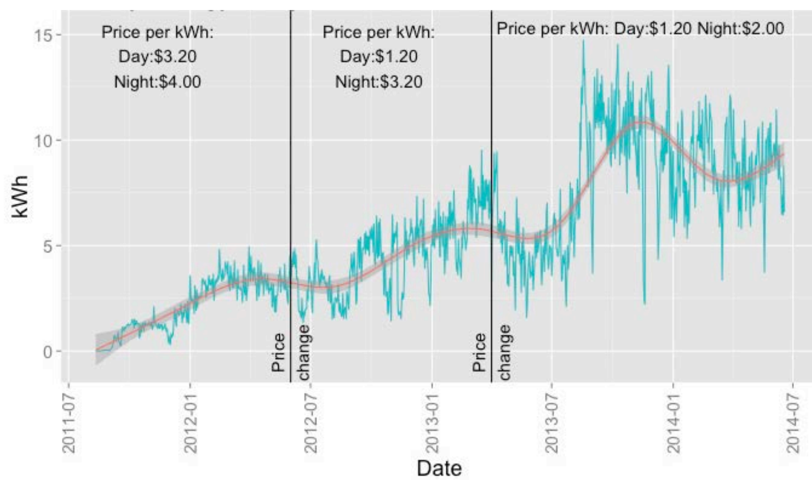


Figure 2: Daily energy usage for a group of SharedSolar customers in Ruhiira, Uganda. Trend line and confidence interval were generated using the generalized additive method. This figure is from unpublished work of the author.

5 Can Low-Voltage Systems Enable Flexible Growth in Consumption?

Leveraging Variation in Energy Spending

In rural areas of developing countries, it is often assumed that all people live at approximately the same income level and therefore their spending on energy is fairly similar. This is not always the case, and we found significant differences amongst the customers prior to the deployment of minigrids. Figure 3 shows this variation within the rural area of Ruhiira in Southwest Uganda, using a sample size of 300 households within a population of 50,000. There is more than a 10x difference between the income level of the highest and lowest customers. This is a key point because many times policy decisions are made based on an average expenditure value. Instead, consider a situation where the top decile of the customers in Ruhiira were connected. These customers spend about $9 per month on energy, and it is considerably more profitable for a utility to bring grid electricity to these customers. After these customers are connected, it is considerably cheaper to connect other customers surrounding the first customers.

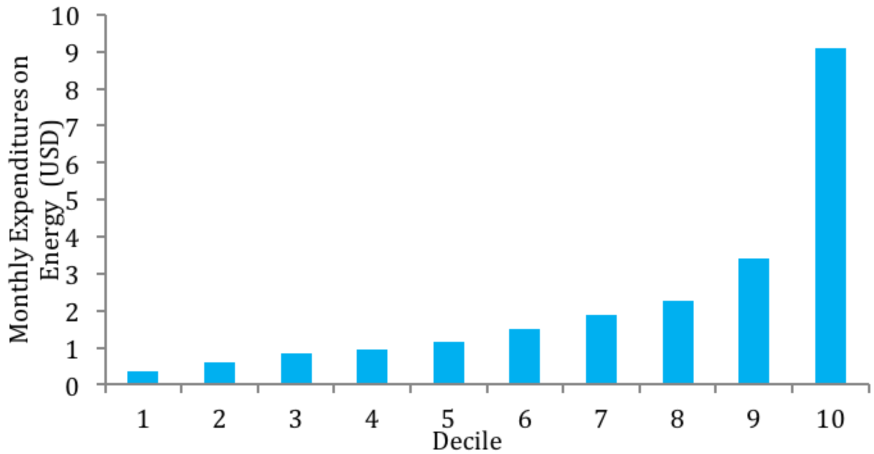


Figure 3: Energy expenses for the region of Ruhiira, Uganda divided into deciles. Includes expenses on fuelwood and charcoal. (Oppelstrup, 2012)

Another example of this is in rural India which is usually considered to have high inequality in incomes. A study looked at incomes from 8 villages and found that the income variation was much larger than would be explained by commonly used tools like the gini coefficient. This is a completely different setting, but Figure 4 looks remarkably similar to Figure 3 from Uganda. This underlines the point that in electricity provision should take advantage of the fact that some customers have a much larger ability to pay than others. These customers can provide a stable source of revenue for the grid or distributed service.

Another way to look at this issue is the percentage of total revenue that a group of customers would provide. In a group of solar micro-grids in Uganda, a cumulative distribution is shown in Figure 5. Note that the largest 10% of customers by usage contributed to about 25% of the total revenue, and the largest 25% contribute about 55%. This differentiated growth over time is worth examining.

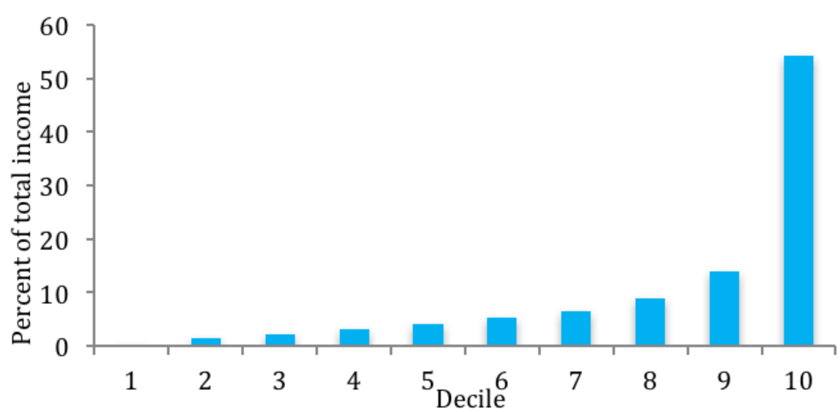


Figure 4: Distribution of household income by decile for selected villages in India.
Data source: Swaminathan & Rawal (2011)

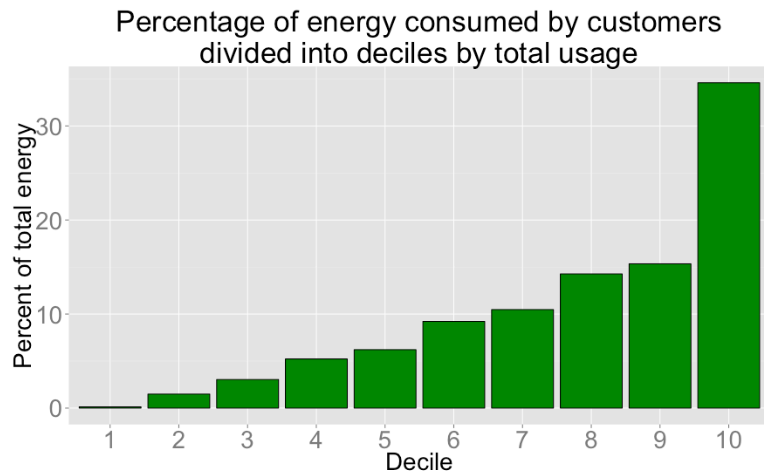


Figure 5: Distribution of energy consumption by decile for SharedSolar micro-grids in Ruhiira, Uganda. Deciles were determined by the total energy usage since the inception of the systems. This figure is from unpublished work of the author.

The consumption data from these solar micro-grids in Uganda is used to divide customers into quartiles, and their demand was tracked over the three-year period in Figure 6. Note that the larger use customers are those that began to engage in some form of entrepreneurial activity over time, even though their initial electricity consumption was similar to that of others. From a minigrid operator perspective it would be very attractive to identify and serve those customers first. However here in this setting, it would have been difficult to identify apriori which customers would have taken a more entrepreneurial approach. Through these low-voltage designs at lower capital costs, it becomes possible within a couple of years to identify where significant consumption growth in occurring and hence create the possibility of prioritizing lower-cost grid supply for that area for more immediate economic impact.

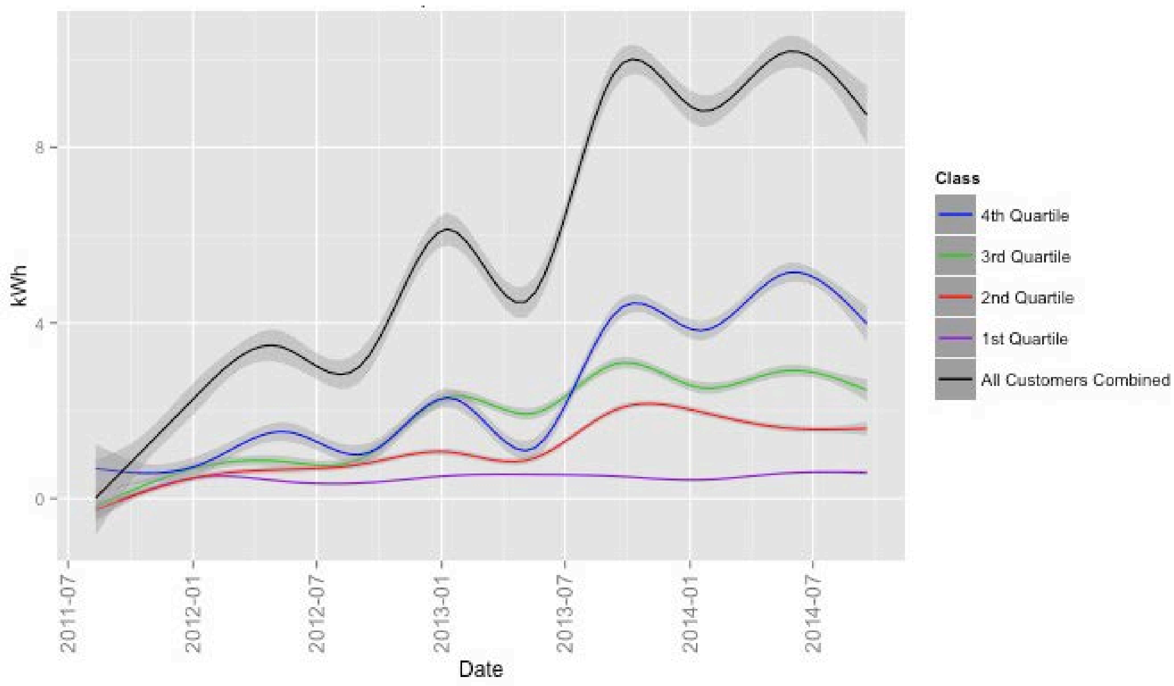


Figure 6: Daily energy usage divided into quartiles for a group of SharedSolar micro-grids in Ruhiira, Uganda. Trend line and confidence interval were generated using the generalized additive method. Quartiles were determined by the total energy usage since the inception of the systems. This figure is from unpublished work of the author.

Entrepreneurship and Capital Constraints

Another important way to consider the issue of growth is at the customer level. In rural areas without electricity, solar home systems are becoming increasingly popular because they provide good lighting and cell phone charging at an affordable cost. However, they do not allow the customer to seamlessly increase their consumption and at the same time the investment is locked in regardless of the customer ability to modulate their expenditure given seasonal income and expenditure variations and possible shocks. Moreover, having the ability consume more for income generation with just having to pay the tariff for consumption as opposed to making a large separate capital expense, could in effect reduce the barrier to entry for the business and also de-risks the activity.

Conventional grid supply if reliable and if available as intended certainly has the ability to provide flexible growth in consumption at tariffs much lower than those viable in the Sharedsolar deployment. A careful examination of how off-grid systems, minigrids and grid systems allow business generation is needed.

At the SharedSolar micro-grid site in Ruhiira (Uganda), an appliance financing scheme was implemented to facilitate large purchases. Twelve-month loans were provided to customers with no interest, but a premium was charged on electricity as a finance charge. Refrigerators were financed for five customers, and the results of this rather small scale experiment were nevertheless instructive. We found a nearly three-fold jump from 5 kWh/ month to 15 kWh/month for three of the five customers that had financed refrigerators. While there is quite a bit of monthly variation, a key observation was that the electricity for the refrigerator use was being primarily paid for through ancillary income generation activities (small business) as a result of the purchase.

6 Productive Use and Low Voltage Systems

Amongst policy makers as well as the political leadership of a country, there remains a strong interest in identifying how energy or electricity plays a role in income generation. The question while certainly of academic interest, is more than just of academic interest. It is central to the lives of the poor, and it is central to the economic growth of the country and it is central to the lending institution that might provide a loan to build the electricity infrastructure. Indeed it would be desirable to seek the greatest return on early investments and presumably this would lead to a virtuous cycle in financing more infrastructure. On the other hand, trying to decide what to prioritize first needs some clear metrics for making that decision.

If nearly all of the electricity demand is purely residential and remains that way, then one can imagine that the overall impact on income growth may be low. 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 and goals are identified, those policies would suggest certain kind of investments to be more appropriate. For example, for irrigation, round the clock power may not be needed and this would allow for solar systems without storage to be readily deployed, and these are significantly lower in cost. Services sector might have large negative impacts from disruptions and hence might care more about reliable 24-7 power while willing to pay a premium for that service in energy charges. Industry on the other hand might require both low-cost and might be willing to adapt to predictable reliability.

What implications does this have for viable low-voltage designs? AC minigrids where there is no storage and the instead of a battery enabling dispatch, it might be possible to schedule available power to one or more loads when the power available, and when no or insufficient power is available, then all loads are shut off. Indeed, this is only possible with loads that are not critical and also loads that care only about a certain daily (or weekly) energy need, but do not care when exactly that energy is received. In a project led by the author (acaciairrigation.org), this was done in the context of several three-phase induction motors that powered irrigation pumps, there is no reason one could not do this for other AC loads that can scheduled, or to supply power to individually owned battery storage on the customer premises. In the later case however the approach described below may be more appropriate since the dc-ac-dc conversions requires could be achieved as below.

Some early work in addressing agricultural needs points to some important avenues of exploration. Many places in Sub-Saharan Africa (SSA) are considered to be food insecure, and this is partially because there are a large number of smallholder farmers using traditional watering or irrigation methods. In fact, if you compare the irrigated area of another developing country, India, to SSA, this difference becomes abundantly clear because 5% of farmland has been irrigated in SSA, compared to 32% in India (NEPAD and World Bank). This difference has a huge impact on the total amount of food produced in these areas, and often limits the types of crops produced as well as the number of planting seasons per year.

Lack of reliable and low-cost power severely constrains the economics of irrigation. Minigrids that utilize battery storage or use fuel become prohibitively expensive for irrigation. A low-voltage approach that is viable here is the distribution of solar PV electricity in form of three phase AC power. The conversion 600V-700V DC to three-phase AC using a variable frequency drive as an inverter is relatively inexpensive. At the same time low-cost induction motors are ideally suited for submersible pump applications. The key to utilization of unstored solar power is the use of a shared power source so that high utilization can be ensured.

With the low costs of solar PV, with appropriate financing electricity can be produced and distributed to the farm at a relatively low cost of 12 cents/kWh, i.e. approaching the busbar costs of grid power. In shallow groundwater areas of Senegal, we observed that a single hectare of irrigated land can generate $8000 in annual revenue from two horticulture crops per year (such as onions and carrots). Here a $15,000 investment in a 7 kW solar PV systems that can irrigate 3 hectares using drip irrigation, can within one year generate at least an equivalent amount in revenue.

Moreover, these systems are also suitable with some added electronics to feed power into the grid when the grid arrives. The absence of batteries keeps the costs low and lifetimes of equipment high.

7 Conclusions and Questions

In conclusion the paper provides a simple classification of low voltage distribution, from LV networks that are part of a larger grid, to mini-grids to off-grid systems. There are several important questions for low-voltage system designs when considering energy access.

Some of the unanswered questions are:

- Do solar home systems allow for emergence of entrepreneurial or small/medium industrial activity?
- What kind of electricity service and the service delivery infrastructure is needed to nurture the non-residential customer? How can one prioritize such infrastructure?
- Can the flexible supply and business model of mini-grids allow for signaling growth and prioritization for the grid? Or would be simply institutionally and financially easier to roll out grid in an entire region?
- Can the combination of smart prepaid metering and appliance finance that minigrids could enable be attractive for higher cost recovery from the grid when the grid arrives?
- How can appliance finance also enable appliance efficiency?

- What is the precise role of public financing in enabling energy access and what is the optimal way to sequence investments?

Bibliography

Alstone, P., Gershenson, D., & Kammen, D. (2015). Decentralized energy systems for clean electricity access. Nature Clim. Change, 5 (4), 305-314.

M. Barnes et al., "Real-World MicroGrids-An Overview," 2007 IEEE International Conference on System of Systems Engineering, San Antonio, TX, 2007, pp. 1-8.

Deichmann, U., Meisner, C., Murray, S., & Wheeler, D. (2011). The economics of renewable energy expansion in rural Sub-Saharan Africa. Energy Policy, 39 (1), 215 - 227.

Eberhard, A., Foster, V., Briceño-Garmendia, C., Ouedraogo, F., Camos, D., & Shkaratan, M. (2008). Underpowered: The State of the Power Sector in Sub-Saharan Africa. World Bank.

Eberhard, A., Rosnes, O., Shkaratan, M., & Vennemo, H. (2011). Africa's Power Infrastructure: Investment, Integration, Efficiency. World Bank.

Foster, V., & Briceno-Garmendia, C. (2010). Africa's Infrastructure: A Time for Transformation. The World Bank.

IEA [International Energy Agency]. (2014). World Energy Outlook 2014.

Lopes, J. A. P., Moreira C. L.and A. G. Madureira, C. L. (2006) "Defining control strategies for MicroGrids islanded operation," in *IEEE Transactions on Power Systems*, vol. 21, no. 2, pp. 916-924.

Martínez, D., & Ebenhack, B. (2008). Understanding the role of energy consumption in human development through the use of saturation phenomena. Energy Policy, 36 (4), 1430-1435.

Mills, E. (2005). The Specter of Fuel-Based Lighting. Science, 308 (5726), 1263-1264.

Oppelstrup, K, Adkins, E. Modi, V. (2012), Rural household energy consumption in the millennium villages in Sub-Saharan Africa, Energy for Sustainable Development, Volume 16, Issue 3, September 2012, Pages 249-259, ISSN 0973-0826,

Pasternak, A. (2000). Global Energy Futures and Human Development: A Framework for Analysis. U.S. Department of Energy, Lawrence Livermore National Laboratory.

Pode, R. (2013). Financing LED solar home systems in developing countries. Renewable and Sustainable Energy Reviews, 25, 596-629.

Smertnik, H., Cohen, I., & Roach, M. (2014). MOBILE FOR SMART SOLUTIONS: How Mobile can Improve Energy Access in Sub-Saharan Africa. GSMA.

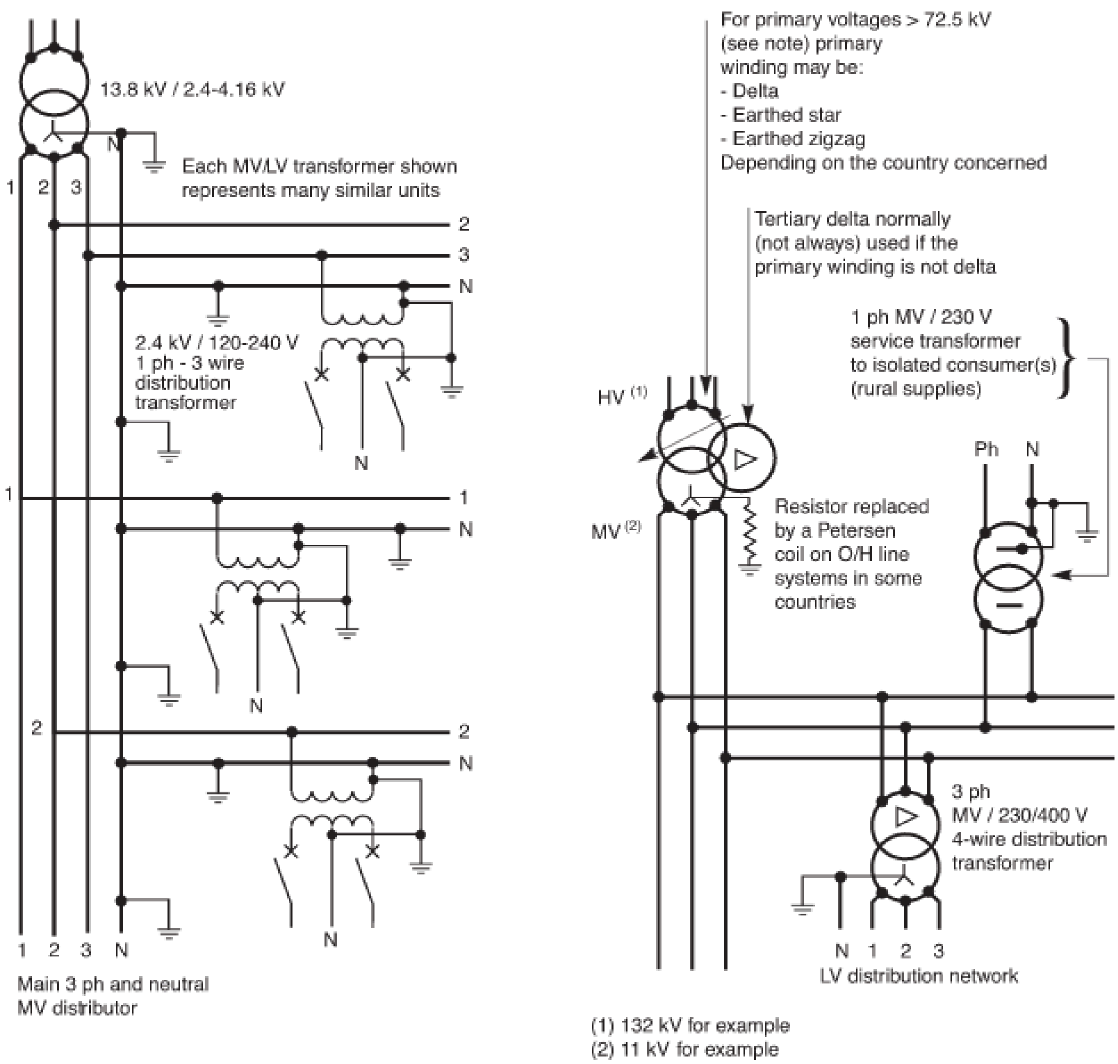
Swaminathan, M., & Rawal, V. (2011). Is India Really a Country of Low Income-Inequality? Observations from Eight Villages. Review of Agrarian Studies, 1 (1).

UNDP [United Nations Development Programme]. (2014). Human Development Reports - Human Development Index (HDI). Retrieved from http://hdr.undp.org/en/content/human-development-index-hdi

WHO [World Health Organization]. (2006). Fuel for Life: Household Energy and Health.

Appendix A: Typical Architectures for the Low-Voltage Systems in a Grid

The figure below is reproduced from www.electrical-installation.org. This is a collaborative platform organized by Schneider Electric. Various possibilities for low voltage distribution emanating from the MV network are shown on the right side of each of the two figures below.



Note: At primary voltages greater than 72.5 kV in bulk-supply substations, it is common practice in some European countries to use an earthed-star primary winding and a delta secondary winding. The neutral point on the secondary side is then provided by a zigzag earthing reactor, the star point of which is connected to earth through a resistor.
Frequently, the earthing reactor has a secondary winding to provide LV 3-phase supplies for the substation. It is then referred to as an "earthing transformer".

Appendix B: Synopsis of a Mini-grid deployment in Africa (SharedSolar)

SharedSolar is a smart solar micro-grid system that has been deployed in Uganda and Mali since June 2011. The goal of SharedSolar was to provide grid-like electricity as a service, and observe consumption growth provided electricity supply was reliable and tariffs charged were at cost recovery rates (if the entire installation and procurement had been at scale and not at the costs incurred in the pilot).

By creating a micro-grid as opposed to individual solar home systems, the idea was that electricity could be provided as a service, and given multiple users, a higher capacity could be allocated to individual customers, recognizing that not all customers would use their allocated capacity at the same time. In addition, there is a local management structure in place to ensure that the supply/demand and battery were well managed. The management system ensured some minimum level of service to all in case of lower solar resource, and ensured that supply was based on pre-payment. The SharedSolar system aims to address these two main needs through a software controlled metering system. Customers pre-pay for electricity from a vendor, and this eliminated the need for a complicated billing system. The software was set up to communicate with the individual customer meters, and power and daily energy limits were preset for each customer. In addition, different tariffs are set for daytime and nighttime to encourage daytime usage for the solar system.

The customer payment system entailed customers buying electricity units from a local vendor who then kept a small percentage as a commission. The vendor in turn purchases credits from a local technician who then deposits the money into a bank account. A schematic of how this system is shown below.