Scalable Solar dc Microgrids

On the Path to Revolutionizing the Electrification Architecture of Developing Communities

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Scalable Solar DC Microgrids – A Way Forward to Revolutionize the Electrification Architecture of Developing Communities

There is a worldwide focus on the electrification of developing regions as evident by the sustainable development goals (SDG) of United Nation. Particularly, SDG - 7 aims to ensure universal access to affordable, reliable, sustainable and modern energy services for all by 2030. Because of these sustained efforts, worldwide over 1 billion people have gained access to electricity since 2000. During this course, the electrification architecture of developing regions has taken different forms ranging from extensive utility grid extensions to the limited off-grid solutions. Off-grid solutions generally offer a cost-effective and lower up-front cost alternative in comparison to utility grid extension, therefore, are deemed more suitable for developing economies. In developing economies, these off-grid electrification solutions have evolved from individual solar home-based systems to the community-based microgrids in the pursuit of achieving higher efficiency and reliability at a village scale. Community grids responsible for the electrification of developing regions are further categorized based on architecture, type of generation and mode distribution. Natural abundance of solar resources in most of the developing regions in South-East Asia and Africa, coupled with the diminishing costs of solar PV panels, advancements in the battery industry and advent of power electronics technology has made solar photovoltaic (PV) generation an attractive alternative to the conventional electricity generation. Compared to traditional AC distribution based microgrids, DC microgrids when implanted with DC generation, DC distribution and DC loads exhibit significantly higher efficiency due to the omission of unwanted AC to DC or DC to AC conversions. Due to these advancements, today PV- based DC microgrids have paved their ways in practical deployments and are being regarded as the most optimal electrification solution for developing economies.

Despite all these advancements, the world is not currently on track to meet the global objectives of SDG-7 and today number of un-electrified people is more than what it was in 2000. Although the conventional schemes for rural electrification are being largely deployed as a stop-gap measure for energy poverty eradication, however, owing to their limited potential, these schemes are not sufficient. With the growing population and associated electrification requirements, there is the need of a highly robust, systematically efficient, technologically advanced, economically feasible, and widely adoptable electrification solution that can be scaled in a bottom-up manner and can support micro-financing for enhanced rates of electrification. This paper highlights the need for rural electrification and subsequently presents the overview of various schemes for rural electrification. A detailed analysis of various architectures of Solar PV- based DC microgrids existing in practice or literature is presented with their respective pros and cons. These architectures mainly include centralized architectures, partially distributed and highly distributed architectures as discussed in the subsequent sections. The analysis concludes that Scalable solar DC microgrids have the tendency to offer a viable solution for future rural electrification implementations and can be regarded as a way forward to achieve the objective of universal electricity access.

Need for Rural Electrification

Reliable access to electricity and its consumption rates are the key indicators for the socio-economic standing of any community. The significant availability of electricity, even at very basic levels, is extremely crucial for human well-being and social resources development. On the contrary, unavailability of electricity hampers basic human rights like access to clean water, health care delivery, education facilities, and proper lighting, thereby, enhance the poverty and significantly deteriorates the quality of life. According to the International Energy Agency (IEA), unfortunately, around 1 billion people throughout the world that constitutes nearly 13% of the global population lack access to electricity. It is also estimated that around 87% of the people lacking access to electricity are the residents of rural areas. According to the statistics of United Nations Department of Economic and Social Affairs (UNDESA), around 90% of children in Sub-Saharan Africa are studying in un-electrified schooling facilities, and another 27% of village schools in developing Asia including India and Pakistan do not have access to electricity. One such remote school near the valley of Naran in Pakistan is shown in figure 1, where students of a primary school are deprived of the basic education facilities like access to well lighted, heated and ventilated classrooms. Moreover, basic computing and printing facilities that are considered as a key to advanced learning are virtually absent due to unavailability of electricity. Same is the case with the access to water for these developing regions as nearly one billion people living in these developing communities not have access to clean, safe water for drinking and irrigation purposes. According to an estimate by The United Nations, due to unavailability of electricity driven water pumps, the inhabitants of Sub-Saharan Africa alone spend 40 billion hours per year in collecting water which is equivalent to the annual worth of labour by France's entire workforce. Also, due to unavailability of electricity, more than a billion people worldwide rely on unhealthy resources, like Kerosene for lighting and wood-based stoves for cooking purposes. According to the estimates of the World Bank, breathing kerosene fumes is highly carcinogenic and as dangerous as smoking two packs of cigarettes each day. According to a report by National Geographic, cookstove smoke is extremely life threatening and around 3.5 million people die each year due to the respiratory diseases caused by indoor pollution of wood/biomass-based stoves (approximately three times of mortality rate caused by malaria and 2.3 times of mortality rate caused by HIV/AIDS).

Figure 1. A Primary School in Naran Valley, Pakistan without access to electricity and basic education facilities

The substantial provision of electricity to these inhabitants can not only reduce alarming fatality rates but can also contribute to improved standards of living including better health, education, agricultural, industrial and employment opportunities. In addition, electrification of these regions through green and environment-friendly energy resources will help in reducing climate change and deforestation rates. Along with social benefits, there are remarkable business opportunities in the energy markets of these developing regions due to the global focus on energy poverty eradication and associated initiatives, e.g. sustainable energy for all (SE4ALL), and "Lightning Africa". Since, human development, economic stability, and social growth of these regions are coupled with the access to electricity, therefore, electrification of these developing regions is the need of the hour to attain the socio-economic benefits associated with the easy access and reliable availability of electricity.

Current Status and Brief Overview of the Existing Practices for Rural Electrification

Over 1 billion people have gained access to electricity since 2000 among which around 220 million were provided access to electricity between 2010 to 2012. The number of people gaining access to power has been accelerating since 2010 to around 118 million each year. These efforts are more pronounced in developing Asia, where around 870 million people have gained access to electricity since 2000 with India as a major contributor for providing access to roughly 30 million people each year in between 2010 to 2016. Also, for the very first time in recent years, electrification rates in Africa have become on par with the growing population. Remarkable efforts of Bangladesh, Ethiopia, Kenya, and Tanzania, led them to expanded electricity access by at least 3% of their population annually between 2010 and 2016.

The main source of electrification during this all course has been the extension of utility and national grid interconnection of these remote villages with a large dependence on fossil fuel. Electrification via grid expansion requires the deployments of mega projects including building new power plants and laying long-distance transmission lines. For developing and under-developed economies, these large-scale developments are generally constrained by the limitations of funding resources. Also, with the constant depletion of fossil fuel, increasing awareness about their hazardous impact on the environment, rapidly decreasing prices of renewable energy technologies and advancement in microgrid technology offering a cost-effective alternative in comparison to grid extension, there is a paradigm shift towards the adoption of environment-friendly renewable energy resources for off-grid rural electrification. Over the last five years, a considerable trend has been seen in the renewable based off-grid rural electrification and approximately 6% of the new access connections are based upon renewable energy resources. Out of all renewable energy resources, solar energy has gained more impetus due to natural availability in most of the under-developed areas (most regions in Southeast Asia and Africa receive abundant sunlight i.e. above 5.5 kWh/m^2/day) and gradually decreasing prices of PV panels and batteries.

The adoption of solar energy for off-grid electrification has evolved from standalone solar home systems (SHS) to microgrid based implementations. Standalone solar home systems (SHS) such as shown in figure 2 have been incorporated as a stop-gap measure to provide rural residents with basic electricity in the last decade in many developing countries. These schemes are highly efficient as the generation, distribution and utilization all are in DC form and there are no losses in the form of AC to DC or DC to AC conversions. Also, the design is simpler and cost-effective for a limited level of electrification. These systems generally provide between a few watts to a few tens of watts enough to run one or two LED's along with a mobile charging unit and a DC fan for an average rural house. As a standout example, in Bangladesh alone, 3 million SHS were installed by 2014 and this is growing day by day. Infrastructure development company (IDCOL) by the government of Bangladesh has reported the installation of 4.12 million SHS in the remote areas up to May 2017 through which 18 million people i.e. 12% of total population has been given access to electricity. The projected target of IDCOL is to install 6 million SHS by 2021. The SHS technology is cost effective and relatively easy to deploy in comparison to grid extension alternative, however, these standalone solutions are suboptimal, as, without resource sharing, they do not take advantage of electricity usage diversity at a village scale. If the power produced by an individual household is higher than its local requirements than extra power undergoes wastage after the battery is fully recharged. Moreover, due to unavailability of resource sharing feature, these schemes have limited electrification capabilities and are not feasible for something demanding like water filtration plants/ irrigation pumps, school computing loads or health care units for a village. Therefore, such schemes cannot provide electricity beyond subsistence level living and cannot contribute for the significant improvement in terms of quality of life.

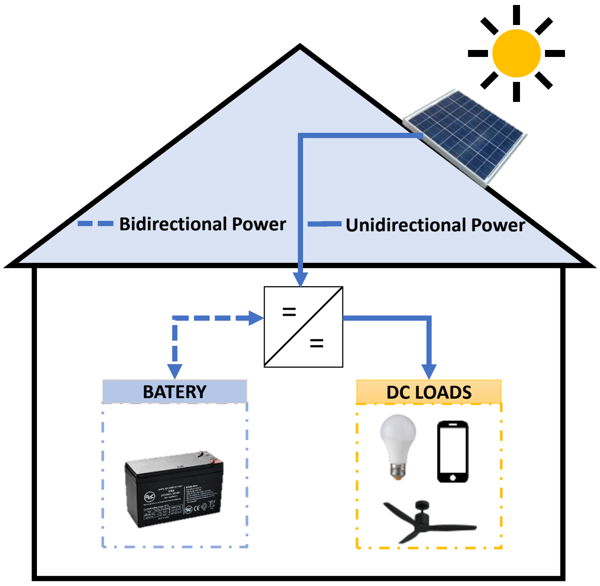

Figure 2. Schematic Diagram of a PV- based Solar Home system (SHS)

The Advent of Solar PV- based DC Microgrids

Although SHS provides a low upfront cost and relatively simpler off-grid electrification solution, there are several limitations to this approach. It cannot support larger community loads due to prohibitively large solar panels and storage requirement for rural occupants in the developing regions. Even with the smaller systems, the levelized cost of electricity (LCOE) is generally high due to lack of resource sharing capabilities. Alternatively, Wind/solar/fossil fuel based islanded microgrids are becoming very popular for rural electrification of developing regions due to their ability to support electrification beyond substance level living and capability to extract the benefit of usage diversity at a village scale. Three major aspects of microgrid design are critical and need to be optimized for making them the best suit the electrification of remote communities. These mainly include a) generation technology, b) mode of distribution and c) architecture for the placement of generation and storage resources.

Conventional resources of generation including fossil fuel-based generation; in particular diesel-based generation systems result in carbon emission and are not considered as an attractive solution for electrification due to their adverse effects on the environment. Moreover, the levelized cost of electricity and operation cost for such diesel-based electricity generation systems are higher and unviable for low-income communities. Over the last two decades, the renewable energy technology has gained worldwide interest as an effective alternative to reduce the dependence on fossil fuels and to avoid their adverse effects on climate change. Therefore, renewable energy resources, in particular, wind and solar energy generation are being largely adopted by microgrid practitioners due to their green and environment-friendly nature. Among all other renewable technologies, installations based upon solar energy extraction using Photovoltaic (PV) systems are more successful due to the natural availability of sunlight, relatively simpler schemes of installation, environment-friendly nature and noise-free operation. The consistent reduction in PV panel prices, Feed-in-Tariffs (FiT) and favorable governmental policies to incorporate renewable energy resources have also encouraged the domestic consumer to invest in this technology to contribute towards sustainable electricity generation. Also, battery technology has become mature and allowing deeper discharges and longer life at a lowering cost, therefore, PV/battery based microgrids can be considered as an optimal choice for future electrification projects.

Solar photovoltaic (PV) produces DC, batteries store DC and most modern loads are now DC, which allows local power generation and distribution through DC microgrids with source closely matching the load profile. Compared to traditional AC distribution, DC microgrids are significantly more efficient due to no DC-AC or AC-DC conversion when implemented with distributed generation (DG). These systems have an end-to-end efficiency of around 80% (for DC loads) compared to AC microgrids which are less than 60% efficient. Along with higher efficiency, DC microgrids and associated distribution have the inherent advantage of less conductor usage for distributing the same amount of peak power in comparison to AC distribution. Therefore, the cost associated with distribution conductors can be substantially reduced using DC distribution. Also, DC distribution is more resilient from power quality issues and its reliability is relatively higher in comparison to AC distribution. Therefore, Due to their inherent simplicity, higher power quality, enhanced efficiency and straightforward controllability, DC microgrids are preferred over AC microgrids for rural electrification applications. These all factors favor PV/Battery based DC microgrids for practical deployments and today they are regarded as an optimal choice for rural electrification applications.

Since their inception, Solar DC microgrids are being regarded as a game changer for transforming the power scenario of remote communities. It is believed that the government subsidized, and public-private partnership based solar microgrids have the potential to do much more than providing basic electricity. These community microgrids have the potential to create opportunities for business and employment by powering schools, medical care units, water filtration plants, agriculture pumps, telecom towers, and many other micro-enterprises. These universal objectives can be attained only through the proper tailoring, design, and selection of a suitable microgrid architecture which favors a local energy economy with higher degrees of scalability and adaptability. An overview of the existing architectures in practice or in literature along with their pros and cons has been discussed in the following sections.

Centralized Architecture of Solar DC Microgrid

Figure 3 shows the topological diagram of a typical centralized DC microgrid architecture used for many rural electrification implementations. Such an architecture in which generation (PV panels) and storage (batteries) resources are placed at a central location is referred to as central generation central storage architecture (CGCSA). CGCSA has a unidirectional flow of power from a central location with solar PV generation and storage to households. A single DC-DC boost converter is required for maximum power point tracking (MPPT) of PV output and stepping up the voltage to microgrid distribution voltage level. At the consumer end, another DC-DC converter is required to step down the microgrid voltage level to household devices level.

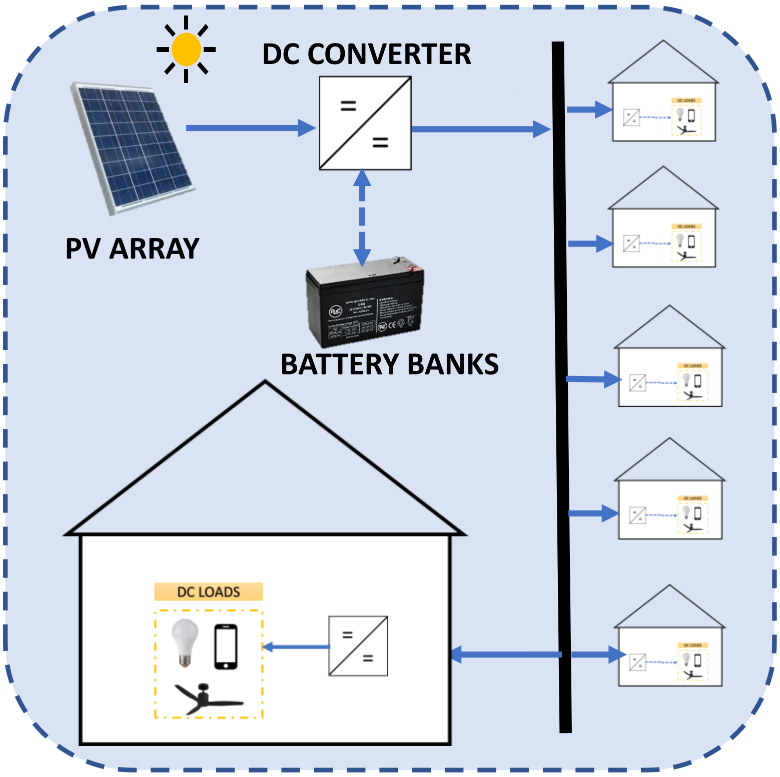

Figure 3. Central Generation Central Storage Architecture (CGCSA) of Solar DC microgrid

Prominent practical implementations for rural electrification through CGCSA of solar DC microgrids include micro-solar plants in Chhattisgarh, by Chhattisgarh renewable energy development agency (CREDA) in India. CREDA has deployed 576 solar based DC microgrids with a cumulative capacity of 2.15MW, serving around 31000 customers in remote areas. Another very successful commercial-scale solar microgrid is the Mera Gao Power (MGP) in India that involves central PV generation and central battery storage with distribution at 24V DC to subscribing houses. The subscribers of MGP may consume up to 5W of DC electricity (enough to power an LED light and a mobile-phone charging point) for 8 hours in a day. It is reported that MGP has over 0.1 million subscribing households spread across 400 villages. Similarly, in 2012, Uttar Pradesh and Renewable Energy Development Agency (UPNEDA), installed 1 kW DC microgrids in 11 districts covering around 4,000 houses. The Jabula project in Cape Town, South Africa is another successful model, where Zonke Energy installed a PV/battery based centralized solar DC micro-grid (750WP) to serves nine families residing in informal settings with basic electricity.

In all the above mentioned practical deployments, the centralized architecture of PV/battery-based DC microgrid is used in which energy is generated and stored at a centralized location. This energy is then delivered to subscribing households via distribution conductors and therefore, distribution losses are associated with the delivery of energy. The distribution losses in this architecture depend upon the number of subscribers, power levels to be distributed, distribution voltage level and size of mass-produced conductor used for distribution. Generally, line losses reduce at higher distribution voltages and the wider area conductor size, while the system exhibits lower distribution efficiency and higher line losses with the increasing number of connected households, higher power levels to be delivered at individual household, lower distribution voltage and lower conductor area used for distribution. The central positioning of the resources is generally beneficial from the perspective of control, where overall generation and storage level (state of charge) are reliably monitored. However, this results in higher distribution losses which become more apparent at higher power levels due to the increasing number of subscribers, household power or community load requirements. Therefore, powering a high power communal load is unviable in centralized architecture from distribution losses perspective. Figure 4 shows the distribution efficiency variations of a typical village in South Asia with the variations in power delivery to individual households (W), a number of connected households (N) and voltage levels at a typical distribution conductor size of American wire gauge (AWG-2). It is evident from the figure that distribution efficiency decreases drastically (at lower voltage levels which are considered safe more village-level electrification) with increasing power levels, thereby making the application of community load practically infeasible in the centralized architecture. Considering the example of —Mera Gao Power (MGP) in India, which provides only 5 W of DC power at 24V to each subscribing house, with a limit of 0.2 amps— enough to power two LED lights and a mobile phone-charging point [18, 21]. Although "small power" is beautiful, it is unable to drive high power community loads and contribute to the uplift of the society. Due to the very limited power supply, such a scheme is unlikely to alleviate poverty in rural areas or contribute to significant improvements in their socio-economic circumstances.

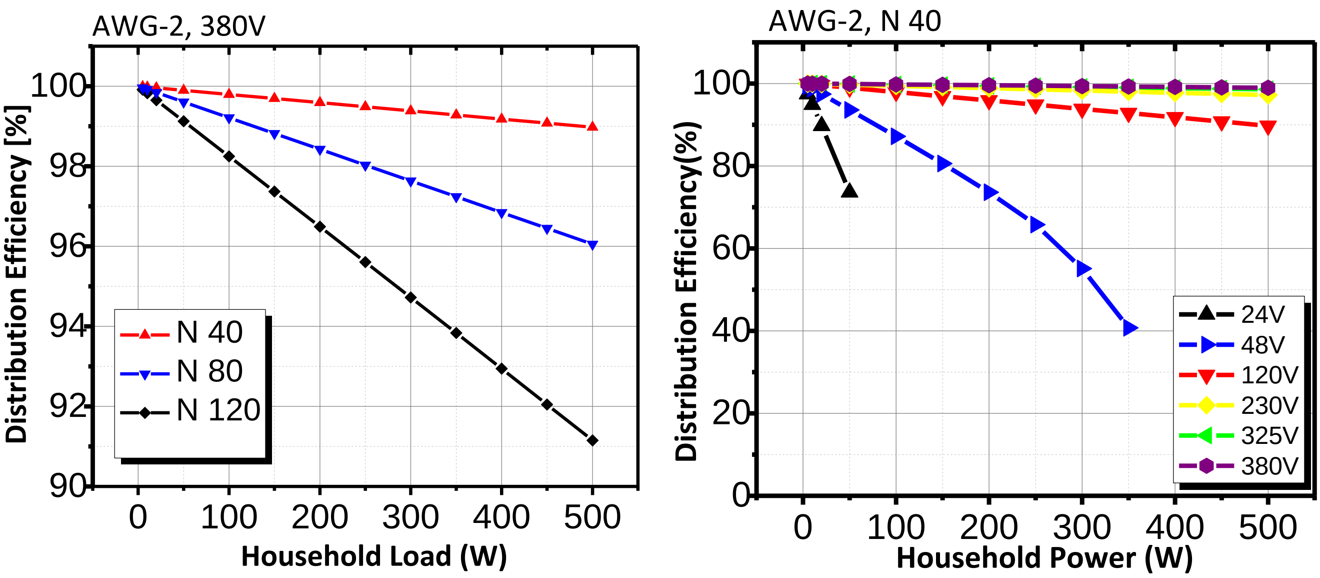

Figure 4. Distribution Efficiency variations of CGCSA with power provisioning variations at an individual household (W)

a) as a function of the number of subscribing households (N) **b)** as a function of the number of distribution voltage level (V)

With the increase in population or number of subscribing households, CGCSA offers rigidity in terms of future expansions due to non-scalable and non-modular nature of power processing equipment (DC- converters). Also, generation and storage resources are generally non-scalable due to the requirements of high-cost synchronization equipment. Therefore, such architectures require central planning of the resources with a top-down approach. The major drawback associated with the top-down planning of CGCSA is that its generation and storage capacity have to be designed as per peak power requirements of the load, thereby increasing the upfront capital cost of installation. For instance, power provisioning to high power communal loads including water filtration plant, computing load of a school or load of medical equipment in a healthcare unit results in a substantial increase in the required capacity and associated cost of the installation. Therefore, such centralized schemes cannot incorporate micro-financing for wide-scale deployments. Moreover, the utilization factor of resources is generally lower due to centralized planning requirements. For instance, at the daytime, when there is enough production by the PV panels and lighting load requirement at houses is comparatively negligible, the excessive power generated by the PV panels cannot be utilized optimally after the storage system has fully charged. Thereby, excessive power will be wasted within panels making the overall scheme essentially sub-optimal in terms of resource utilization. Therefore, distribution efficiency, non-scalability, lower utilization factor and higher upfront cost requirements are the major limitations in narrowing down the scope of centralized architecture for global energy access realization.

Distributed Architectures of Solar DC Microgrid

To minimize the limitations of a centralized architecture, researchers are working on scalable architectures that are either partially or completely distributed in nature from the perspective of PV generation and battery storage resources placement at a village scale. Distributed and scalable architectures with bottom-up approach can enable organic growth of microgrid, and therefore, can potentially empower the local communities for sustainable development. Due to their distributed nature, they have minimum distribution losses in the path and therefore, can provide higher power deliveries at individual households. Also, with resource sharing and power aggregation features, they can sustain high power community loads, without dedicated power generation. One such architecture is termed as a central generation distributed storage architecture (CGDSA) as shown in figure 5. By distributing the battery storage system at individual consumer nodes will result in reduced distribution losses, while the distributed power may be intelligently stored or consumed at the load end using household power management units (PMU). This will not only impart scalability to the overall structure in terms of future capacity enhancement but also the provision of energy storage at local houses results in higher efficiency compared to CGCSA. The communication among the distributed storage resources at various households can be done through GSM and resources at individual households can be pooled up together for communal load application. However, the presented architecture uses centralized PV generation, because of which higher distribution losses are associated with the distribution of generated energy.

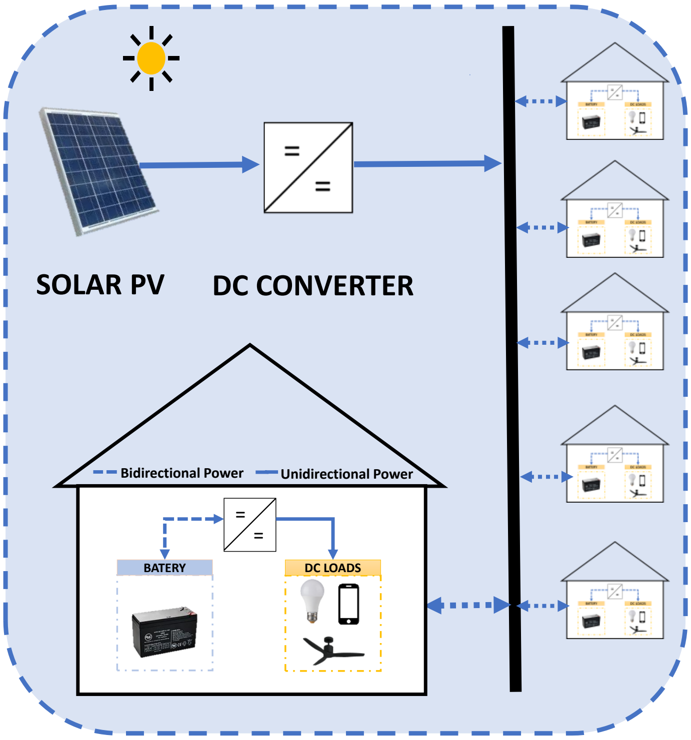

Figure 5. Central Generation Distributed Storage Architecture (CGDSA) of Solar DC microgrid

The distribution losses associated with the generated energy can be further reduced using either partially distributed architecture (PDA) or highly distributed architecture termed as distributed generation distributed storage architecture (DGDSA) of solar DC microgrid. In PDA of solar DC microgrid, the consumer and generation modules are distributed throughout the village, thus formulating a partially distributed architecture. The generating modules have PV generation and battery storage resources at their disposal that can be used to power up their local load as well as to supply power to consuming nodes. Therefore, partial distribution of both generation and storage resources and peer to peer electricity sharing through GSM-based communication between power management units (PMU) of generating modules (houses having PV generation, battery storage, and local load) and consuming modules (houses having only local loads without any generation or storage facilities) results in reduction of distribution losses. The advantages of PDA are mainly a reduction in distribution losses and modularity in a structure which allows scalability for future capacity enhancements. Also, power from generating modules can be pooled up for community load purposes, thereby making PDA a suitable architecture for economic uplift of the society.

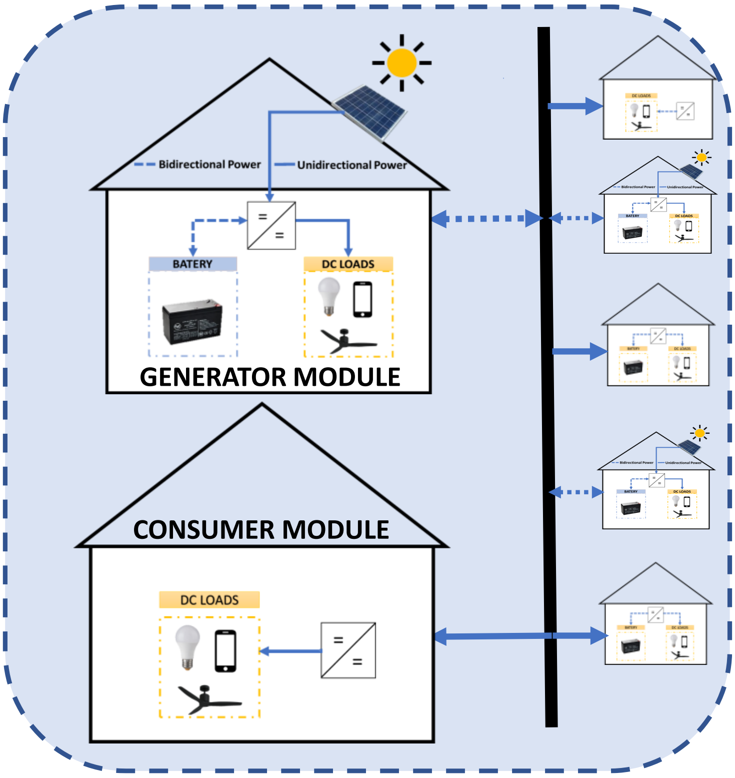

Figure 6. Partially Distributed Storage Architecture (PDA) of Solar DC microgrid

The distribution of generation and storage resources results in a reduction of overall distribution losses and also imparts scalability to the architecture. Therefore, a highly distributed architecture of solar DC microgrid having PV generation and battery storage at each individual house termed as distributed generation and distributed storage architecture (DGDSA) is shown in figure 7. Each household has its own PV generation, battery storage and local DC loads. Further, bidirectional power flow capability is available in each household through bidirectional DC converters to supply or demand power based upon the local conditions of generation storage and utilization. Therefore, in such a system, each household can work independently as well as it may share resources with the community. PV generation and battery storage resources are designed according to local load profile and therefore, most of the times each household in DGDSA will be operating in islanded mode. Consequently, the losses associated with the distribution of energy from generation point to the utilization point will be minimized while all the household load requirements will also be fulfilled simultaneously. The distribution losses will occur only when there is a need for power-sharing among multiple households or when there is a communal load demand.

The architecture has the built-in advantages of (a) higher efficiency because of distributed generation and distributed storage, (b) modular scalability for future expansion, (c) efficient aggregation of power for larger loads even with limited roof-top PV, and (d) delivery to communal entities as rural schools and basic health units by pooling power from individual household units without dedicated (large) generation, Furthermore, the distributed nature of the proposed DGDSA makes it independently scalable in its planning and operation. Therefore, such a highly distributed architecture does not require centralized planning of resources; rather it can be planned in a bottom-up manner such that more and more number of subscribers can be added within the architecture without excessive modifications/ replacements in the existing structure. The coordinated resource sharing among dispersed generation and storage resources, therefore, formulates a swarm of energy which has higher potential than the uncoordinated centralized resources in the microgrid structure.

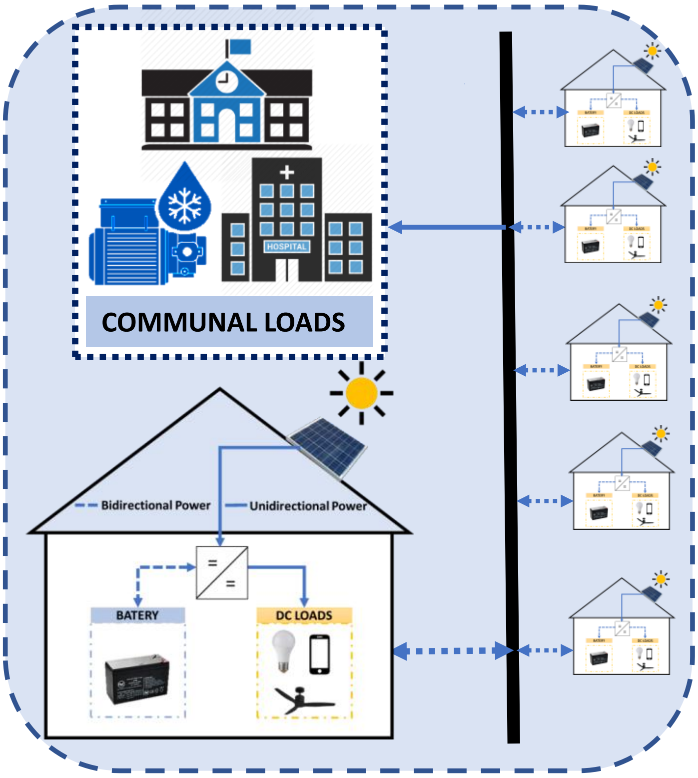

Figure 7. Distributed Generation, Distributed Storage Architecture (DGDSA) of Solar DC microgrid

From the sustainability perspective, distributed architectures are highly suitable for micro-financing opportunities for private investors/public-private partnerships. Distributed architecture also has the potential to create an energy economy in the village through regulated energy transactions among multiple households. This will not result in business opportunities but also will open many horizons for local employment e.g. for bill collections, for maintenance of distributed PV resources. Therefore, along with the capability to bring socio-economic uplift in terms of communal load driving capability, distributed architectures have the potential to empower the local population by creating indigenous business and employment opportunities.

Comparison Matrix

The electrification architecture of developing communities has taken different form since after the beginning of rural electrification era and focus of governments and international organizations on universal energy access. These mainly include electrification via utility grid, standalone solar home systems, diesel generator- based electrification and solar microgrids- based electrification as tabulated in Table I. Each electrification solution has some salient characteristics associated it out of which economic viability is one of the key concerns for developing economies with constrained funding resources. The ability to provide higher amounts of power for subscribing households as well as for community load applications is another key feature that quantifies the potential of the scheme for contributing towards socio-economic uplift. Various possible power provision levels for the village scale electrification have been tabulated in Table II. Figure 8, shows the mapping of various electrification solutions from the perspective of economic viability and power provision capability. It is apparent from the discussion of various architectures that distributed solar DC microgrids exhibit higher level of scalability and can be designed with bottom-up approach resulting in lower up-front cost requirements and higher economic viability for developing regions. Also, lower distribution losses in the path of power delivery and bi-directional resource sharing capability enable the architecture to support higher power loads for community benefits. A brief comparison of other salient characteristics of various electrification schemes including scalability, modularity, utilization efficiency, the potential for energy micro-economy, the potential for poverty alleviation and legal challenges are also shown in Table III. Since the cost and the affordability are the main drivers for adaptability, therefore, a cost comparison of various architectures for a village of 40 households is highlighted in Table IV. These village level microgrids are generally sustained through microfinancing or private sector investment, therefore, a subscription-based cost analysis is also highlighted in Table IV. Monthly Charges are calculated for paying back upfront and O&M cost including batteries replacement for a period of 25 years.

Table I. Various In-Practice Solutions for the Electrification of Developing Regions

Type of Solution	**Option**
Utility (National) Grid	A
Standalone Solar	B
Diesel Generators	C
Centralized Solar Microgrids	D
Distributed Solar Microgrids	E

Table II. Typical Power Provisioning Levels for Village Scale Electrification

Typical Power Provisioning (levels)	**Details**
1	Light/mobile phone charging up to 8 hrs a day
2	24/7 Light/mobile charging
3	Light(s) + mobile charging + house loads (Fans etc.)
4	Light(s) an + mobile charging + Fan(s) + larger communal loads
5	All loads (including industrial)

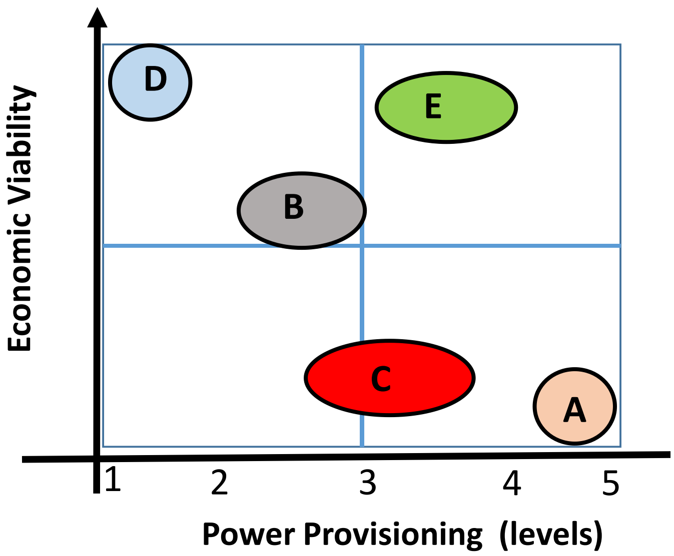

Figure 8. Mapping of Various Architecture from Power Provisioning and Economic Viability Prospective

Table III. Characterization of Various In-Practice Solutions for the Electrification of Developing Regions

Other Aspects	**A**	**B**	**C**	**D**	**E**
Scalability	Low	Low	Low	Low	High
Modularity	Med.	Low	Low	High	High
Utilization Efficiency	High	Low	Low	Med.	High
Communal Loads	High	Low	High	Low	High
The potential for Energy Micro-economy	Low	Med.	High	High	High
The potential for Poverty Alleviation	High	Med.	Low	Low	High
Legal Challenges	Low	Med.	Low	Med.	Med.

Table IV. Estimated cost of Various Architectures of DC Microgrids for a Village of 40 Households.

Architecture	**Load per house (24/7 provision to subscribers)**	**Capital Cost (USD.)**	**Capital + 25 years O&M Cost (USD.)**	**Subscription Charges per user per month for payback in (USD. /Month)**		
				3 years	**6 years**	**9 years**
CGCSA	1 light and mobile phone charging unit (5W).	2020	4550	1.4	0.8	0.6
DGDSA	3 Lights, 1 fan, charging unit (30W per house)	9110	24900	6.3	4.2	3.1
	3 Lights, 1 fan, charging unit and Communal load (30W per house +500W)	9525	25510	6.6	4.5	3.3
Standalone Production and Consumption (No Microgrid)	3 Lights, 1 fan, charging unit (30Wper house)	10310	27905	7.1	4.9	3.3
	3 Lights, 1 fan, charging unit and Communal load (30W + 500W)	11100	29815	7.7	5.3	3.8

Potential Challenges in Practical Deployments of Distributed Microgrids

Although the scalable architecture allows for the efficient utilization of distributed resources in a highly scalable manner, some challenges associated with larger deployments persist. From a practical implementation perspective, there can be potential challenges for the distributed placement of resources. Space barriers along with the maintenance of converters and cleaning of PV panels at individual households are some of the practical challenges that need to be addressed for successful practical implementations. Bi-directional power flow metering and theft monitoring issues must also be considered for future installations. High-level distribution of resources poses a challenge with respect to safety and protection due to the increased likelihood of short circuit contribution from multiple paths within the microgrid. Therefore, future large-scale practical implementations must also include an intelligent protection scheme capable of real-time load flow and short circuit analysis for adaptive relay settings. From an economics point of view, such a distributed model is highly suitable for micro-financing opportunities for private investors / public-private partnerships. In order to enable energy trading among multiple households, there must be a mechanism to monitor energy transactions among neighboring houses. Although energy trade mechanism will formulate a local energy market and will be helpful for empowering rural inhabitants, however, it will require an information and communication layer at neighborhood levels to ensure monitoring of energy exchange. A practical solution to these technical challenges along with successful business models and financing solutions may enable wide uptake of the distributed solar microgrids for achieving the enhanced level of energy access in coming years.

Conclusion

The conventional schemes of electrification are limited in their potential either due to economic constraints or due to their inability to sustain high power loads. Alternatively, scalable solar DC microgrids designed through a bottom-up approach offer a financially viable solution along with the ability to sustain high power loads for community benefits. Therefore, scalable architectures of solar DC microgrids don't just provide access to basic electricity; rather they have the potential to act as a catalyst to economic growth and improved livelihoods. A proportionate and meaningful electrification of developing regions can be achieved through the implementation of scalable solar DC microgrids coupled with financing and policy commitments on a broader scale. Thus, scalable solar DC microgrids having distributed nature and bottom-up design can be regarded as a way forward to realize the global objectives of universal energy access.

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For Further Readings

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