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A critical look at present pathways and challenges

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The Long Road to Universal Electrification: A Critical Look at Present Pathways and Challenges

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Abstract: Nearly 840 million people still lack access to electricity, while over a billion more have an unreliable electricity connection. In this article, the three different electrification pathways—grid extension, centralized microgrids, and standalone solar-based solutions, such as pico-solar and solar home systems (SHS)—are critically examined while understanding their relative merits and demerits. Grid extension can provide broad scale access at low levelized costs but requires a certain electricity demand threshold and population density to justify investments. To a lesser extent, centralized (off-grid) microgrids also require a minimum demand threshold and knowledge of the electricity demand. Solar-based solutions are the main focus in terms of off-grid electrification in this article, given the equatorial/tropical latitudes of the un(der-)electrified regions. In recent times, decentralized solar-based off-grid solutions, such as pico-solar and SHS, have shown the highest adoption rates and promising impetus with respect to basic lighting and electricity for powering small appliances. However, the burning question is—from lighting a million to empowering a billion—can solar home systems get us there?The two main roadblocks for SHS are discussed, and the requirements from the ideal electrification pathway are introduced. A bottom-up, interconnected SHS-based electrification pathway is proposed as the missing link among the present electrification pathways.

Keywords: rural electrification; solar home systems; microgrids; SDG 7; multi-tier framework

1. Introduction

Universal electrification is a monumental challenge facing humankind today. Just under a billion people globally lacked access to any form of electricity at the end of 2017 [1], an (inadequate) improvement since 2000, when there were 1.7 billion people without electricity [2]. Three main solutions were tried, with varying degrees of success, in the last decade to increase the umbrella of electrification. These are:

1. Grid extension.
2. Off-grid micro (or mini-) grids.
3. Standalone household level solutions, such as pico-solar and solar home systems (SHS).

While solar-based standalone solutions have gained prominence in the last few years, the overall electrification efforts have not been rapid enough. The UN also took note of the progress on SDG 7, saying it “remains too slow to be on track to meet the global energy targets for 2030” [3].

1.1. Relevance and Scope of This Article

More than 920 million people have gained electricity access since 2010 [4], and the majority (more than 750 million) was in the form of national grid-based electrification (derived from [4,5]). In recent years, India accelerated largely on grid-based electricity and made massive strides in its rural electrification program, but still has some way to go before each household is electrified [6]. On the other hand, off-grid electrification solutions, specifically off-grid solar-based solutions, have also been responsible for providing basic electricity access to no less than 279 million people as of 2019 [7]. These different electrification pathways were effective in their own ways, and there is a need to compare them and highlight their relative advantages and shortcomings.

In this article, the three main electrification pathways currently in use are analyzed while discussing the relative merits and demerits for each pathway. Special attention is paid to the solar-based off-grid electrification. This is because off-grid renewable energy-based electrification emerged in the last decade as a mainstream, cost-competitive alternative to grid-based electricity. For instance, between 2011 and 2016 alone, more than 133 million people benefited from off-grid renewables [5]. Specifically, off-grid solar solutions have recently been stated to make up 85% of all off-grid energy solutions [4]. We critically look at some of the most pressing problems that off-grid solar-based electrification is/will be facing in achieving scale en route to universal electrification.

The contemporary tools used to quantitatively evaluate the most economically viable solution are usually based on population density and techno-economic feasibility. However, these are limited to specific locations and case-studies, as seen in the studies presented in [8] (Kenya), [9] (Ethiopia), and [10] (Ghana). On the other hand, this article compares the electrification pathways at a qualitative level, while additionally discussing the requirements from an ideal electrification pathway.

Furthermore, it must be noted that technology is only one part of the larger puzzle of electrification. Business, policy, and sociocultural aspects also need significant attention, as noted in [11,12]. However, the scope of this article is largely limited to the technical and technological considerations of electrification.

Another caveat to consider when discussing electrification is the perceived benefits in economic development almost equivalently assumed to follow electrification. It must be cautiously noted that electrification in and by itself is merely the enabler of economic transformation; it is the usage of electricity and associated services that is the actual driver [13]. The correlation between human development and energy usage (as discussed in [14]) that drove investments and energy access policies so far in sub-Saharan Africa only holds if energy access is viewed through the lens of the services it enables and is tackled in the broader context of development (including water, food, health, and economic development).

1.2. Electrification Ladder

The electricity demand of a user increases with time, a phenomenon well captured in the literature in the past [15,16]. This phenomenon can be visualized in the form of the so-called energy ladder, as referred to in the literature before [17]. Specifically in the context of electrification, it is also referred to as the electrification ladder [15,18]. Figure 1 illustrates the concept of the electrification ladder. At the lowest rung is an unelectrified household with no access to electricity, represented by a fossil-based fuel source (e.g., kerosene lamp). Higher rungs of the ladder represent the increase in the number of appliances, and therefore, the overall electricity demand.

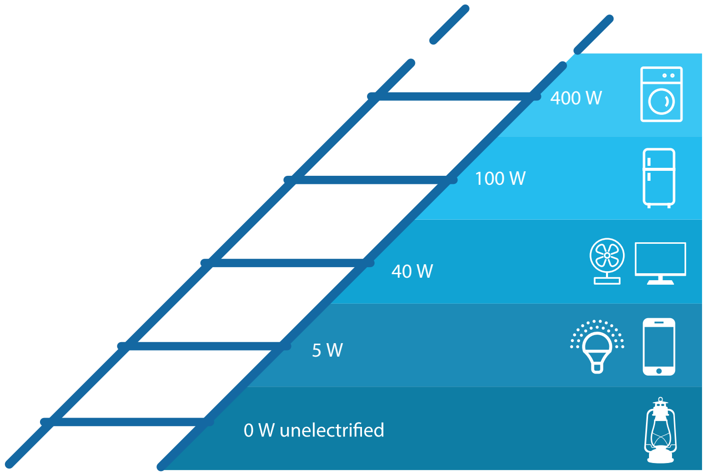


Figure 1. Conceptual illustration of the electrification ladder. As a household scales up the ladder, the electricity demand increases through the addition of higher power (or greater number of) appliances relative to the preceding rungs of the ladder. The power levels of the appliances are indicative only.

1.3. Multi-Tier Framework for Measuring Electricity Access

In the past, governments have often defined electricity access as a connection to an electrical grid, whether or not that connection is reliable. Additionally, large sections of the people (e.g., a whole village) have also been called electrified if a small percentage of the households is electrified [18]. Until the previous decade, electricity access was largely looked at as a have or have-not condition. However, such oversimplification is a dangerously narrow view of understanding and acting towards the electricity access problem. Such binary metrics were therefore considered insufficient, and a multi-tier framework (MTF) was proposed in [19], which captures the multi-dimensional nature of electricity access. Table 1 presents the MTF as described in [19].

In terms of the electrification ladder mentioned in Figure 1, the climb up the ladder can now be alternatively seen as the movement across the tiers of the MTF.

Table 1. Multi-tier matrix for measuring access to household electricity supply. Sourced from [19].

	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Energy and peak power rating	>12 Wh & >3 W	>200 Wh & >50 W	>1 kWh & >200 W	>3.4 kWh & >800 W	>8.2 kWh & >2 kW
Availability (h/day)	>4	>4	>8	>16	>23
Availability (h/evening)	>1	>2	>3	>4	>4
Reliability	—	—	—	<14 disruptions per week	<3 disruptions per week
Quality	—	—	—	Voltage problems do not affect the use of desired appliances	
Affordability	—	—	—	Cost of 365 kWh/year <5% of household income	
Legality	—	—	—	Bill is paid to the utility or authorized representative	
Health and Safety	—	—	—	Absence of past accidents and high risk perception in the future	

Contribution

This article contributes to the current scientific discourse on the global problem of electricity access through the review of the main current electrification pathways, while highlighting their limitations and relative (de)merits. The authors also present their perspective on a decentralized electrification paradigm with potential benefits that could overcome the challenges faced by the present electrification pathways.

Outline

This article contains seven sections. Section 1 introduces the problem of universal electrification with the 3 electrification pathways presently in use. Sections 2–4 discuss each of the electrification pathways in detail. Section 5 presents the significant challenges hindering the state-of-the-art SHS from becoming the electrification pathway of choice in the long run. Section 6 describes the requirements from an ideal pathway that can overcome the current challenges and discusses the comparative qualities of each electrification pathway. Finally, Section 7 summarizes the article with closing thoughts on universal electrification.

2. Pathway 1: Grid Extension

Grid-based electricity refers to a household deriving its electricity from a local network that is connected to the larger transmission network, where the grid is typically powered by large centralized power plants. Grid extension refers to the act of expanding the national grid's network to provide electricity access. Grid extension includes installing medium voltage distribution lines as well as adding new connections to the households needing electricity access [20].

Grid extension has historically been the most common way to provide electricity access to un(der-)electrified regions and communities. Apart from being a common approach, it can also be the most cost-effective way to provide electricity access at very high levels of electricity demand, e.g., for tier 4 and tier 5 electricity access.

However, grid extension is cost-effective only if the target region has a certain population density and energy demand. Otherwise, the extension efforts are almost certain to incur losses. For example, 55% of all customers serviced by Kenya Power and Lighting Corporation (KLPC) spend less than $3 a month on electricity, pushing the payback period of a typical KLPC grid connection to 44 years, even for higher levels of consumption [21]. The high investment costs for grid extension were estimated in the order of €22,750/km for transmission line and €12,000/km for distribution line in most African countries; in comparison, the grid-based retail electricity tariffs in these countries could range from €0.04/kWh (subsidized) to over €0.23/kWh (non-subsidized) [22]. Inadequate revenues also result in progressive deterioration of the reliability of the transmission and distribution network. Unsurprisingly, the compounding effects of these inadequate revenues led to 81% of sub-Saharan African utilities reporting net financial losses in 2013 [23]. Unfortunately, the present reality is that conventional African utilities tend to run a loss every time they connect to a rural customer [21]. Electricity access without sufficient consumption is detrimental to the idea of grid-based electrification, as evidenced in a study of African utilities, which found that only two of them have fully recovered their costs [13].

While the lack of affordability by the consumers can hamper the viability of the national grid as an electrification option, there are also examples where the infrastructure lags the people's ability to pay. There are several countries where people above the poverty line, who could potentially afford to pay for electricity but still do not have access due to infrastructural issues. For example, it was estimated that in sub-Saharan Africa, 120 million people were living above the poverty line without access to electricity [2]. Other factors, such as topographical issues, regulatory hurdles, and sparse populations, can also make the investment and maintenance of grid extension less favourable compared to off-grid solutions [2].

Fieldwork carried out in 2017 in India also highlighted the complex issues at the grass-roots level related to the limitations of national grid outreach [24]. Figure 2 depicts a "powerful" image; it captures the harsh reality of electricity access for a rural household in a state in Northern India. A single solar panel can be seen on the rooftop that also has cow dung cakes drying in the sun, which will be used as cooking fuel once dried. Making up the powerful irony in the picture are the grid lines passing tantalizingly close to the house, which had no grid-based electricity access until 2017 despite the presence of the grid in the region for several years.

Figure 2. So close, yet so far: A rural household in Aligarh, Uttar Pradesh (India) with installed SHS. Grid lines have passed close to the house for years, yet the household was without any grid-based electricity until 2017. Photo credit: Gaurav Manchanda.

Competition with Off-Grid Renewables

A significant factor that has led to grid expansion losing out on the cost-effectiveness front for rapid electrification is the rise of the off-grid solutions. In particular, solar-based off-grid solutions, such as pico-solar SHS, have enjoyed tremendous success in recent years as the electrification solution of choice. This has mainly been due to the massive drop in prices of most pico-solar and SHS components. For example, PV price has fallen by more than 80% from 2009 to 2017; LED lights and Li-ion batteries have dropped by 80% and 73% respectively between 2010 and 2016 [5]. Moreover, national grids often heavily depend on fossil fuels for power generation and are therefore counterproductive to progress on other SDGs, such as SDG 13 (climate action) and SDG 11 (sustainable cities and communities).

However, it is usually a complex task to declare grid extension better or worse than an off-grid alternative. Investigating the viability of grid extension for a particular target location must take into account not just its distance from the existing grid, but also the expected energy consumption and relative off-grid standalone system costs. Figure 3 simplistically illustrates the conceptual cost curve as a function of distance assuming a certain energy demand and fixed off-grid system cost. The point where the grid extension costs and off-grid costs meet forms the breakeven distance for that particular case. To the left of that distance, the grid-extension option is more economically favourable, while an off-grid solution is favourable to the right of that breakeven distance.

Figure 4 depicts a conceptual comparison of breakeven annual electricity consumption as a function of upfront SHS system costs for a given target region. It is assumed that different target regions would have different mean distances from the grid leading to different curves. The annual electricity consumption as outlined by the MTF is also marked for the various tiers on this conceptual graph. Grid extension will be a cheaper option if the annual consumption of a household in the target region is more than the breakeven electricity level given by the curve. Although a conceptual illustration, it can be seen that the capital SHS costs need to be much lower to be able to justify a standalone system for higher tiers of consumption.

Therefore, it can be said that the precise determination of the viability of grid extension for the electrification of a particular target location depends on multiple factors as seen in Figures 3 and 4. Furthermore, other non-technical factors, such as policy, regulations, and topography could pose additional challenges for grid extension.

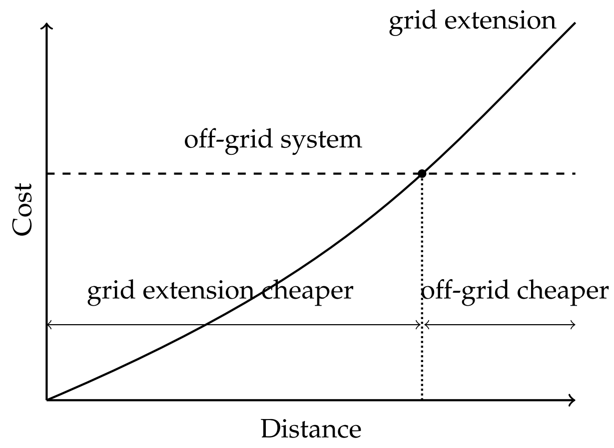


Figure 3. Conceptual comparison of off-grid system and grid-extension cost-curves as a function of distance from the existing grid (adapted from [20]). Off-grid system costs are independent of distance from the existing grid.

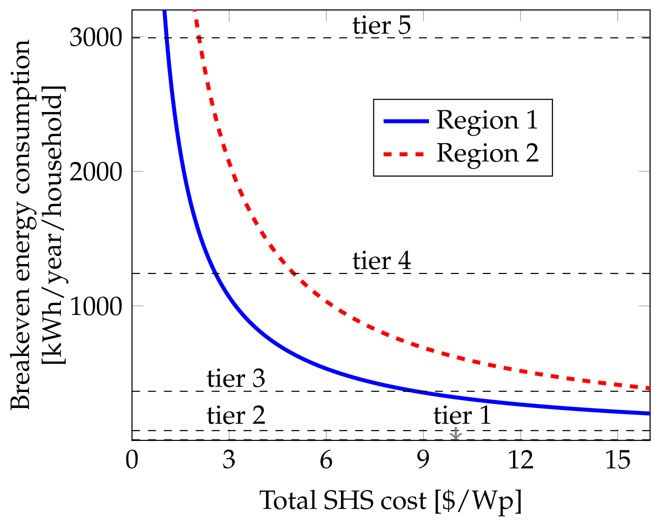


Figure 4. Illustrative breakeven annual consumption as a function of SHS upfront costs for two different regions (adapted from [25]). The different tier consumptions of the MTF are also marked for reference. Tier 1 is not clearly visible given the scale of the y-axis, as the annual energy consumption for tier 1 level is merely 4.38 kWh.

3. Pathway 2: (Off-Grid) Centralized Microgrids and Mini-Grids

3.1. Clarification in Terminology

When it comes to off-grid electrification, there are no universally accepted definitions for, or distinctions between, mini-grids and microgrids. Several different definitions exist. For example, the IEA has defined mini-grids as "small grid systems linking a number of households and other consumers" [26]. Although not specified in the context of off-grid electrification, the National Renewable Energy Laboratory (NREL) defined microgrids as "a group of interconnected loads and distributed energy resources that acts as a single controllable entity with respect to the grid" [27]. In the context of electrification, generally, mini-grids and microgrids operate isolated from the grid. Hence, this electrification pathway is referred to as "off-grid".

Some definitions also take into account power levels, although these limits may also vary from one definition to another. For example, the Alliance for Rural Electrification (ARE) defines mini-grids as having capacities ranging from 10 kW to 10 MW, and microgrids as being similar to mini-grids with generation capacities of 1–10 kW. In general, mini-grids and microgrids are standalone electrical power systems that serve multiple consumers through wired connections, powered by PV modules, diesel gensets, or/and wind turbines [20]. A microgrid has a connotation of being smaller in power capacity, as also seen in some of the power capacity-based definitions above.

Note:

For the remainder of this article, the term "microgrids" will be consistently used in the context of off-grid electrification. However, many of the arguments and ideas discussed could also be interchangeably applied also to mini-grids, especially when centralized power generation is considered.

3.2. Centralized Microgrids

Microgrids for off-grid electrification can further be classified based on the power generation technology used, e.g., solar PV, biomass, micro-hydro, wind, diesel, etc. Hybrid microgrids are also possible, which use two or more power generation technologies. Energy storage technologies, such as batteries, are frequently used in microgrid projects to improve the availability of power supply. The most common storage technologies are lead-acid and lithium-ion batteries. Sometimes, diesel is also used to replace the battery in a hybrid microgrid, although this option incurs running fuel costs. Usually, the power generation is centralized, i.e., the power generation occurs centrally, and there is a distribution network responsible for supplying power to the consumers. In this article, the main focus is on solar PV as the power generation technology of choice, owing to its historically decreasing prices, modular nature, and ease of installation.

An example of a centralized microgrid architecture is shown in Figure 5. The term centralized refers to the central power generation and storage, which is shown in Figure 5 in the form of solar PV and battery storage. Additionally, given the recent proliferation of the so-called super-efficient DC appliances [28], the microgrid depicted in Figure 5 assumes a DC architecture.

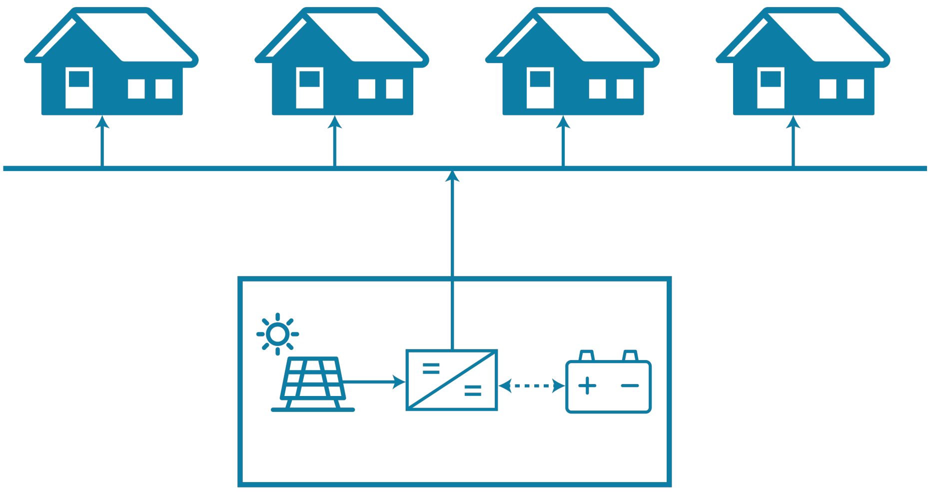


Figure 5. An illustration of a centralized (DC) microgrid architecture. The term centralized refers to the central power generation (solar PV) and storage (battery). Each house is assumed to have a set of (DC) loads.

Centralized vs. Decentralized

Microgrids-based off-grid electrification is often referred to as being decentralized. It must be cautiously noted that the classification of these systems being decentralized stems from collectively viewing the myriads of such microgrids juxtaposed with the central national grid. In that specific context, these microgrid systems can be together viewed as autonomous, and hence a decentralized way of delivering electricity. However, in terms of architecture, rural microgrids are usually centralized with central power generation and storage. Therefore, these off-grid microgrids were classified as centralized microgrids in this article.

3.3. Microgrids vs. Grid Extension

Where national electricity grids fail to reach, microgrids can step in with several benefits. Microgrids score over grid extension over several categories, as described below.

1. **Transmission and connection costs.** One of the biggest gains for microgrids in comparison to grid extension comes in the form of minimizing transmission costs, which can be up to 40% of the total grid-based electricity costs [29]. On the other hand, as the microgrids usually serve areas within 5 km of the installation, they incur minimal transmission losses compared to the grid. Typical mini-grid retail tariffs in Africa have seen to range from €0.1/kWh to €1.2/kWh, depending on local conditions and operators [22]. Average per connection capital cost of starting a microgrid was estimated to start from as low as $50, as compared to the average per connection costs of grid extension, which were estimated at $500 [29].
2. **Empowering local population.** Furthermore, traditional national grids are largely a vertically integrated and regulated monopoly. On the other hand, rural microgrids can be highly empowering to the local consumer population, not just in terms of the benefits of electricity itself, but in terms of local entrepreneurship opportunities. These microgrids also have the potential to improve gender equality through greater involvement of women in the value chain [30].
3. **Reliability of power supply.** In terms of reliability, microgrids can often perform better than ailing grids in urban and peri-urban areas of low- and middle-income countries. For example, private sector microgrids have reportedly observed 98% up-time in Tanzania as compared to the national grid's reported usable voltage range availability of 47% in Dar es Salaam [21].
4. **Integrating renewables.** In terms of generating power technology, microgrids are perfectly poised to use renewables, as opposed to grids. Since most of the microgrids are to be installed from scratch, opting for renewable sources of energy, such as solar PV, is much more economical in both capital costs as well as fuel costs. This way, the route to achieving SDG 7 can be without adversely affecting the overall climate targets and hampering the progress towards other SDGs.

   Furthermore, while there are many renewable energy technologies available, solar PV is the most viable and widely suited, as there is abundant sunshine in the electricity-starved regions most of Asia and Africa, except for a few locations due to excessive rains. In comparison, other renewable energy sources, such as (micro-)hydroelectric power, have to depend on site-specific resources, such as a perennial stream.

The efficacy of (rural) microgrids in electrification was established beyond doubt. The undeniable potential, as well as the necessity of rural microgrids, was mentioned in several studies on future scenarios. In one of its scenarios, the IEA estimates 140 million people in Africa to receive electricity access through mini-grids by 2040, necessitating the development of between 100,000 to 200,000 mini-grids [26].

3.4. Microgrids vs. Standalone SHS

Figure 6 shows a comparative plot of the total installed capacity of off-grid solar energy sources for the years 2010 and 2016. A phenomenal growth in capacity can be seen for off-grid solar, underlining a positive trend and a momentum that is poised to continue. Figure 7 shows a similar statistic for the number of people gaining access to electricity through off-grid solar between 2010 and 2016. The remarkable fact is that despite a much smaller number proportion of people affected by the microgrids (nearly 124 million through standalone PV as compared to 2.2 million tier 1 and 2 level PV microgrid and 9 million including hybrid microgrids in 2016 [31]), the total installed capacity of PV microgrids is much more sizable at around 296 MW than SHS at around 215 MW and pico-solar at 58 MW, as seen in Figure 6. This can is attributed to the fact that the installed capacity of the microgrids, which are usually at a community scale, can be much higher than SHS and pico-solar, which are limited to the household level.

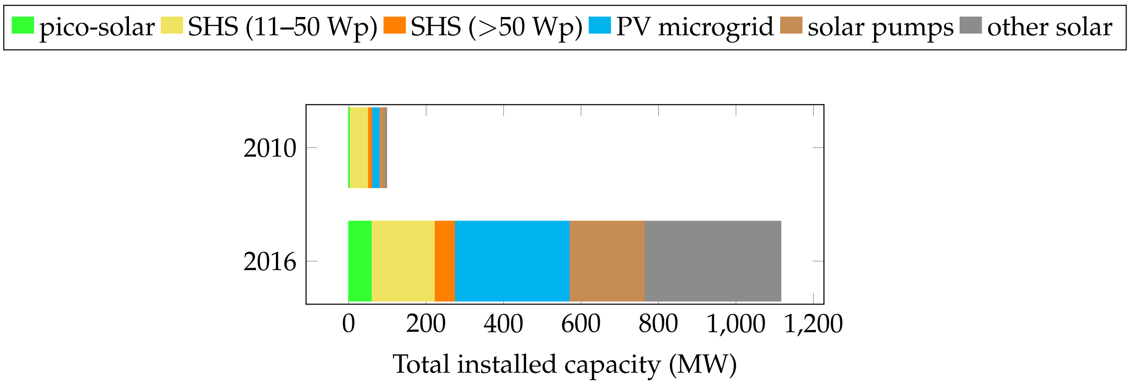


Figure 6. Capacity of different installed off-grid solar energy sources including SHS, pico-solar, solar PV minigrids, solar pumps, and other uncategorized off-grid solar PV applications (data from [31]).

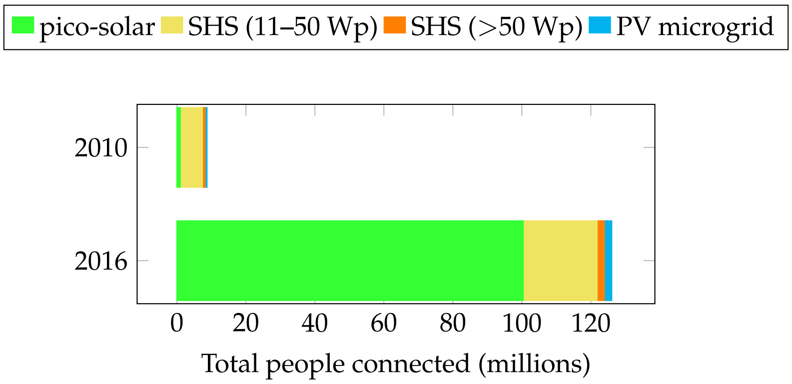


Figure 7. Number of people with improved electricity access to off-grid solar energy sources including SHS, pico-solar and solar PV minigrids (data from [31]).

Compared to standalone systems, such as SHS, microgrids offer multiple advantages, as discussed below.

1. **High power loads.** Higher installed power capacity of the microgrids by definition allows for higher power loads. Thus, people can potentially enjoy higher tiers of electricity access, as opposed to smaller standalone systems, such as SHS or pico-solar products, which often tend to keep the consumers locked in with respect to the choice of appliances.
2. **Load variance.** Higher load variance can be achieved through microgrids as multiple households are connected [32]. This leads to the added benefit of better use of the installed resources, such as PV and battery, provided the given levels of load consumption are commensurate with the installed power capacity.
3. **Productive use of energy (PUE).** Productive use of energy implies the use of energy for supplementing income generating activities [33]. Usually, PUE appliances, such as power tools, pumps, etc. are of higher power rating than basic consumptive household appliances, such as fans, TV, and a small fridge [28]. These are better supported by microgrids than SHS.
4. **Community buildings and loads.** Microgrids are also suited for community buildings, such as schools and hospitals, where a single SHS will not suffice. Additionally, community level loads can be met by microgrids more easily than standalone systems.
5. **Cheaper unit system costs.** Compared to SHS, microgrids can fundamentally attain cheaper unit system costs due to economies of scale. However, the overall system cost can pose a significant challenge in the beginning.

3.5. Disadvantages of Centralized Microgrids

Microgrids also come with a distinct set of disadvantages that are holding back this electrification pathway from achieving its full potential. These demerits are described below.

1. **High capital expenditures(CAPEX).** High CAPEX costs are a major barrier leading to slow uptake of microgrids for electrification. Unlike biomass plants, which have low CAPEX and high operational expenditures (OPEX), PV microgrids have high CAPEX and low OPEX. High CAPEX can be an impediment, especially if the microgrid is operating on a private or community-owned model, as opposed to a utility-owned model.
2. **Arrival of the national grid.** The arrival of the national grid has complicated consequences. On the one hand, the advent of the grid could be a perfect ending to a microgrid story as the microgrid could (potentially) seamlessly integrate with the grid. On the other hand, it could also bring about technical as well as financial consequences. As a thumb rule, grid tariffs are usually lower than microgrid tariffs due to cross-subsidization as well as economies of scale [22]. Additionally, certain technical standards need to be met before a microgrid could connect with the main grid, e.g., voltage and frequency regulation, and islanding capabilities. Microgrids can turn into stranded assets if the arrival of the grid is not planned for. Regulatory frameworks need to exist from the start if the integration of microgrids with the national grid is desired.
3. **Need for demand threshold.** Similar to national grids, albeit, at a lower level, microgrids need a certain demand threshold to justify their initial investment in the network.
4. **Operational involvement with consumers.** Although the OPEX costs are relatively low in PV microgrids, high operational involvement is needed from the microgrid operators in terms of interaction with hundreds or thousands of households for revenue collection. This part is unique to rural microgrids, as opposed to large solar farms where the plant developers have minimal operational involvement. The participation of well-established players has therefore been negligible in terms of rural microgrids as opposed to smaller private entities.
5. **Overall demand estimation.** The peak power rating for the central installation is hinged on the demand estimation of (usually) hitherto un(der-)electrified community. In some cases, the installation might even be oversized to account for the future demand of the microgrid. Lower than expected consumption patterns could lead to a risk of inadequate revenues, while higher than expected consumption could lead to potential blackouts.

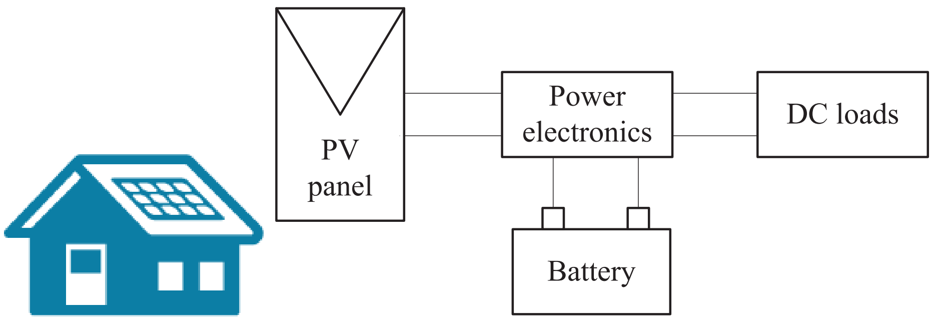
4. Pathway 3: Solar-Based Standalone Systems

This electrification pathway includes solar-based standalone systems, such as pico-solar (solar lanterns) and SHS. SHS are standalone PV systems rated 11 Wp and above, usually not more than 350 Wp and mostly less than 100 Wp [34,35]. Solar lanterns or pico-solar products are defined to have rated PV power of less than 11 Wp [36]. Sometimes, further categorization of SHS and pico-solar exists, based on either wattage (for SHS), such as 11–21 Wp, 21–50 Wp, 50–100 Wp, and >100 Wp, or based on services provided (for pico-solar), such as single light, single light + mobile charging, multiple lights + mobile charging [34]. In any case, it is expected that pico-solar products can enable tier 1 access, while SHS can enable at least tier 2 access.

Figure 8 shows examples of pico-solar and SHS products currently being used in the off-grid market, helping to accelerate (decentralized) electrification. Figure 9 shows a symbolic representation of SHS used in this article along with a schematic block diagram representation. The SHS consists of a PV module, a suitably sized battery, power electronics for power conversion, and a set of DC loads.

(**a**) (**b**)

Figure 8. Examples of a pico-solar product (solar lantern) and an SHS from the company d.light. Images obtained from [36]. (**a**) A solar LED lantern (d.light S30) with 0.3 Wp solar module and integrated 60 lm LED [37]. (**b**) A solar home system with a 40 Wp panel and DC appliances [38].



(**a**) (**b**)

Figure 9. Symbolic and block diagram representations of an SHS. (**a**) Symbolic representation of a household with installed SHS. (**b**) Block diagram of an SHS.

Since pico-solar is limited to tier 1 access only, SHS is a more viable alternative for decentralized electrification, and therefore, discussed in greater detail in the following sections. Installation of SHS has improved the lives of off-grid consumers in multiple ways, e.g., creating job opportunities, enhancing business revenue, unlocking additional work hours, and increasing monthly income, among others [39].

SHS vs. Grid And Microgrids

Present day SHS enjoys several advantages as the pathway of choice in accelerating towards last-mile electrification targets. Some of these advantageous features are discussed below.

1. **Least cost option.** Even though SHS score poorly in terms of levelized cost of electricity (LCOE) ($/kWh) or unit system costs ($/Wp), they are by definition able to offer least total system costs by catering to a single household, as opposed to centralized microgrids and grids, which need to attain a certain scale of consumers to justify lower costs. SHS are an economically more appealing choice when facing conditions, such as long distances from the grid, low density of population, and low electricity demands. Of course, the affordability of the user depends largely on the target regions and specific financing mechanisms available, which is a different topic altogether, and not within the purview of this article.
2. **Last mile connectivity.** Historically, grid-based electricity has often taken the longest to reach the remotest corners of a country. In terms of last mile connectivity, while rural microgrids perform better than national grids, SHS perform even better than microgrids as the electricity demand

threshold is the lowest for SHS. Often, governments themselves subsidize the uptake of SHS to augment the national electrification efforts.

3. **Use of DC appliances.** Many SHS providers are opting for a full DC system to save on conversion losses. BBOXX, a company active in East Africa, supplies its SHS consumers with its in-house portfolio of DC appliances. In Cambodia, the use of AC appliances and inverters is discouraged, and end users are also advised to use efficient DC appliances with their SHS [40]. These so-called super-efficient DC appliances can significantly reduce the strain on SHS size for delivering the same amount of electricity, thereby shifting the total cost distribution of an SHS along with resulting in cost savings [2,15]. Additionally, the extent of the increasingly efficient DC options available in the market today, as catalogued extensively in [33,41], proves further the impetus that DC-based SHS enjoy going forward. More on these efficient appliances is discussed in [28,33].
4. **Better service through technology.** The use of technology, such as data acquisition and remote monitoring can significantly impact consumer satisfaction and uptake, which is otherwise usually a pain-point for SHS. Internet of things (IoT) is increasingly being used for implementing smart SHS to facilitate easy data acquisition and analysis. For example, BBOXX used its SMART Solar platform in nearly 20,000 SHS to better understand the user needs, enabling them to create scalable business models for energy access [42]. This leads to not just better user insights but also faster service and higher SHS user satisfaction.
5. **Rapid growth and adoption.** Scaling up is often easier for SHS as opposed to microgrids, because microgrids are often a customized solution from one installation to another. On the other hand, an SHS (from the same manufacturer) for a given size can be produced over and over given the product demand. This has enabled rapid growth and adoption of SHS. As seen in Figure 7, between 2010 and 2016, the number of people gaining electricity access through SHS went from 7.2 to 23.5 million people [31]. As of 2017, off-grid solar solutions provided improved energy access to 73 million households [36].

5. Present Issues with SHS-Based Electrification

The most directly significant barrier that prevents widespread adoption of SHS is the unit system cost. Technologically, this can be most tangibly addressed only in the form of declining component costs. From a business point of view, it comes down to innovative business models tailored to suit the target region and community. From a policy point of view, subsidies could also play a role. These considerations are outside the scope of this article. However, even if the adoption of present SHS were to scale to a billion units radically, there are still two major drawbacks that will hold back existing SHS from being the perfect pathway towards universal electrification. These issues are discussed in this section.

5.1. Climbing the Electrification Ladder with SHS

Owing to its standalone nature, SHS is dimensioned to cater to a particular level of load demand. Dimensioning or sizing is often a critical exercise; an oversized SHS leads to an expensive system leading to wastage of energy and unaffordability to a considerable portion of the target population, while an undersized SHS leads to insufficient power availability that may cause user dissatisfaction and lower technology adoption rates. Therefore, SHS need to be optimally sized for a given load demand [43].

However, as is clearly shown in the literature and observed in the field, one of the consequences of providing access to electricity is the increase in electricity demand itself. That is, the demand for electricity often increases with time [15,16,44]. Therefore, in time (sometimes, in less than a year), the perfectly dimensioned SHS becomes obsolete and untenable to cater to the growing demands of the user. In other words, a particular SHS size is insufficient to enable the climb up the electrification ladder.

Figure 1 illustrated the concept of the electrification ladder. As a person or household moves up the electricity ladder, the quality and quantity of electricity demand increases, which can also be viewed as movement across the tiers in the context of the MTF. State-of-the-art SHS typically supply up to tier 2 level of electricity, and sometimes to tier 3. Even though a dedicated SHS for tier 3, 4 or 5 could be custom made, often it is not the best solution because:

(i) it would be at the cost of discarding the previously perfectly dimensioned lower tier SHS, as households seldom demand a direct tier 4 or 5 level access and usually climb up the electrification ladder
(ii) at higher levels of electricity demand, the storage costs would significantly drive up the total system costs [43,45].

In general, the level of electrification is often a dynamic requirement as the electricity needs increase with time. The current SHS-based electrification is largely inflexible to this requirement. Appliances for productive use of energy and communal loads, which are also usually commensurate with tiers 4 and 5 of electricity access, can also not be powered with typical state-of-the-art SHS power levels.

5.2. The Paradox of SHS-Based Electrification

State-of-the-art SHS are usually limited to 100 Wp. This leads to a paradoxical predicament as shown in the conceptual illustration in Figure 10, which maps the appliance costs versus power rating space. The highlighted region represents the range of the typical SHS in terms of power delivery and the usual DC appliances used in such an SHS. These appliances are the so-called super-efficient DC appliances.

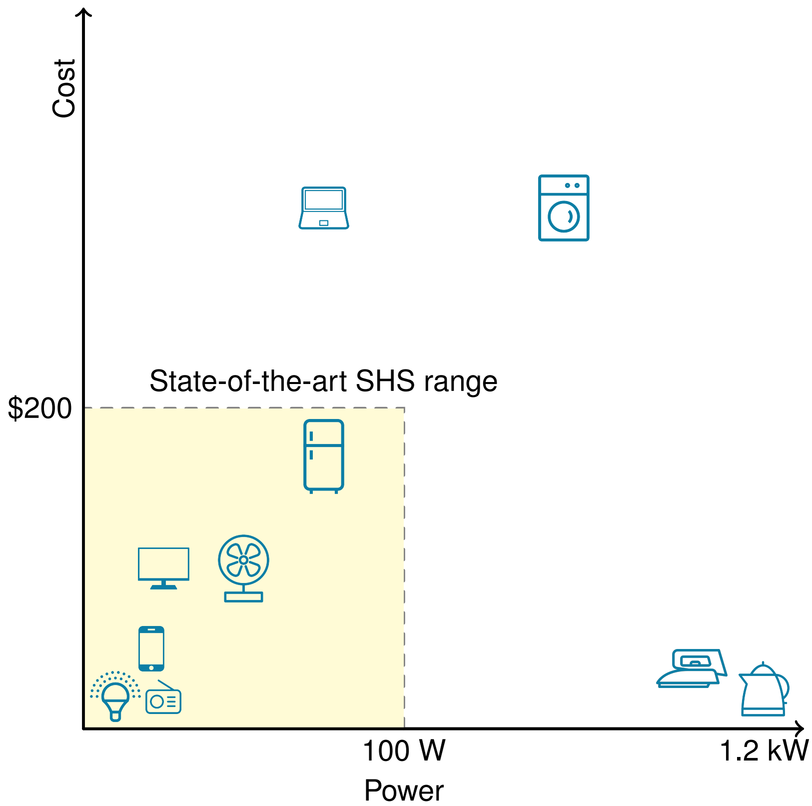


Figure 10. A concept graph illustrating the mapping between power rating of the various home appliances and their costs. Note: the price level is just an indicative number, as the prices differ greatly across vendors and geographies.

Horizon appliances, such as washing machines, are definitely outside the scope of the present day SHS, both in terms of power and in terms of price, as denoted by the icon in the upper right corner in the graph. However, a 70 W laptop charger can be easily powered by a 100 Wp SHS, while the appliance (laptop) itself might be well outside the range of typical appliances afforded by an SHS consumer. Ironically, some appliances, such as the water kettle and rice cookers, are already cheap enough (sub $5–10) for low-income communities to buy, but cannot be powered by the SHS due to the high-power rating of the appliances (e.g., a kW or more for the water kettle). In a Cambodian field study carried out in 2016, inadequate power level has already been noted as a shortcoming of the present SHS. The local users expressed interest in powering water kettles and rice cookers with their SHS. The field study was conducted to mainly find out the future needs of SHS users in rural Cambodia. Figure 11 shows photos from the fieldwork [15].

(**a**) (**b**)

Figure 11. Photos from the fieldwork carried out in Cambodia as part of this PhD project [15]. Photo credit: Thomas den Heeten. (**a**) Simulation game to engage the SHS users on their future electricity needs and appliance wishlist. (**b**) Visual representation to understand the expected times of the future appliance usage.

Considering the above two issues, therefore, the biggest criticism for SHS comes in the form of its impermanence as an electrification pathway. It was often regarded as merely a short-term solution [46]. Despite the undeniable momentum in accelerating up to tier 2 level electricity access, SHS was largely seen as a stopgap solution to provide lighting and some basic appliances until the advent of the national grid.

The deployment of SHS leads to the unlocking of the latent electricity demand of the consumers, thereby paving the way for the need for higher power solutions, such as microgrids and grid extension. On the one hand, the silver lining is that an increased demand might justify the installation of higher power systems, such as centralized microgrids and grid extension. On the other hand, the delays and other roadblocks associated with grid extension and microgrid installation might keep the consumers locked in at a certain tier of electricity access.

In general, from lighting a million to empowering a billion, solar home systems in their present form can only take us part of the way.

6. The Ideal Pathway for Universal Electrification

Now that the three electrification pathways were discussed in detail along with the challenges and opportunities they face, we can think of the ideal pathway for achieving universal electrification. As mentioned earlier, the focus of this article is on off-grid solar-based electrification.

Figure 12 shows the different electrification pathways mapped onto a plot of ease of electrification versus power level. Ease of electrification can be seen as the ease (both in terms of economic viability as well as technology adoption through commensurate level of consumption) with which electricity access can be made available to hitherto unelectrified communities. In other words, ease of electrification can be seen as 'on demand' electrification. Grid extension is almost always an economically unviable solution to electrify the remote, last mile communities. Decentralized solutions, such as pico-solar and SHS, perform much better on the ease of electrification, while the grid performs far better on the power levels. In other words, current electrification pathways present an inherent trade-off between the on-demand electrification versus on-demand power consumption. Centralized microgrids perform somewhat in the middle on both counts as compared to SHS and the grid.

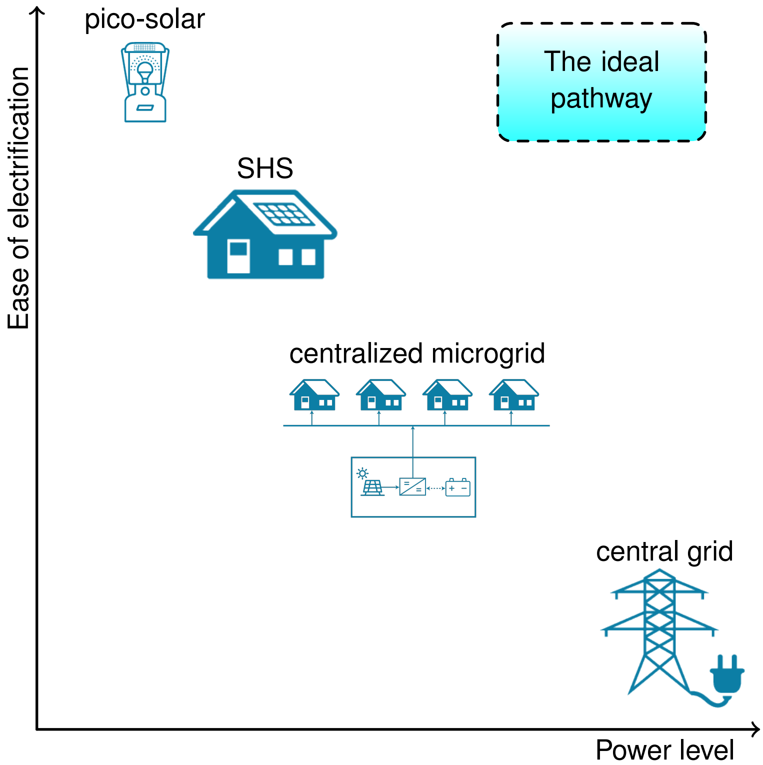


Figure 12. A concept graph illustrating the comparison between the different electrification pathways on a plot of the ease of electrification versus power demand.

The ideal electrification pathway is represented in Figure 12 in the top right corner; it can provide rapid electrification while catering to 'on demand' power consumption commensurate with higher tiers of electricity consumption. This solution has to be as easy for rapid adoption as SHS while addressing the current shortcomings plaguing SHS from becoming a truly sustainable electrification solution. The requirements from such an ideal off-grid solar solution that can overcome the issues mentioned in Section 5 can be listed as follows.

1. **Climbing the electrification ladder.** The solution should be expandable to cater to growing household needs as well as scalable to accommodate increasing numbers of the systems in the off-grid communities.
2. **High power appliances**. The solution should enable the use of high-power appliances.
3. **Retrofitting.** The solution should be able to work with other existing SHS.
4. **Future-ready.** The advent of the electricity grid in the future should preferably not render the present solution completely obsolete.

6.1. SHS-Based Microgrid

In the absence of fundamental technological breakthroughs that can radically affect component costs or choice of energy technology, an SHS-based microgrid can be a means to at least approach the ideal pathway. Figure 13 shows this concept, where a meshed DC grid can be created through the interconnection of existing SHS already operating on DC. Such a microgrid can grow in time, as opposed to a centralized microgrid that is relatively rigid with respect to initial system sizes.

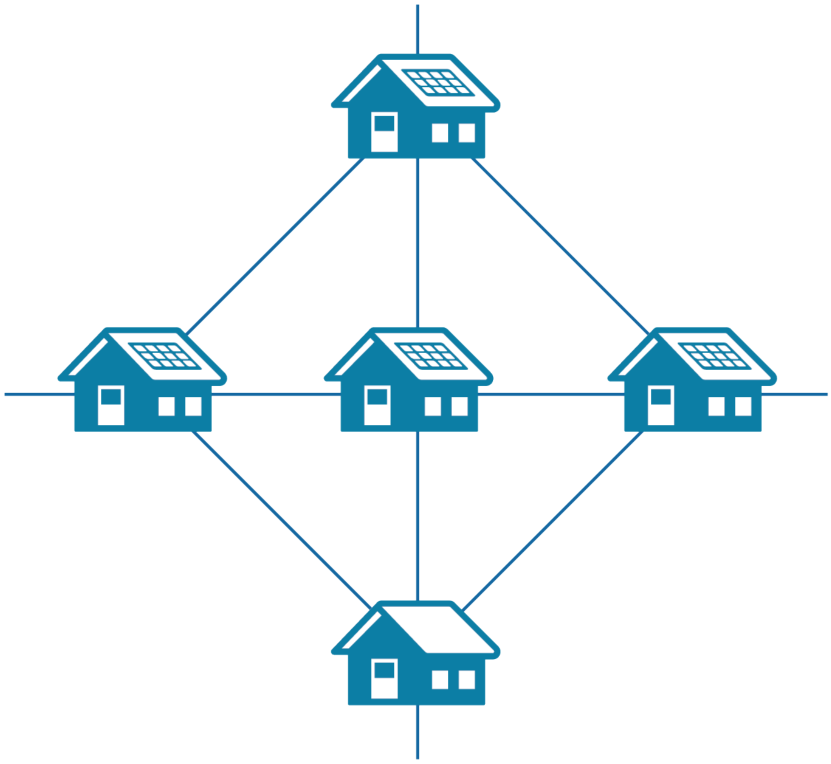


Figure 13. Conceptual illustration of a bottom-up, scalable, interconnected SHS-based meshed DC microgrid [32]. The bottom house is shown without any SHS, indicating the possibility of purely consumptive houses joining such a microgrid.

This concept has seen multiple proponents in recent literature [47,48]. However, the existing projects in practice are mostly limited to tiers 1 to 2 with 12 V battery and 12 V distribution [32]. In order to enable higher tiers of consumption, such microgrids need to make use of higher voltage distribution as it minimizes distribution losses [49]. The quantification of benefits from these microgrids was detailed by the authors of this article in a recent publication [32].

Such bottom-up, organically growing microgrids that are born out of the interconnection of existing SHS can enable energy sharing. Additional advantages of such microgrids would include reduced system sizes as compared to standalone SHS and the capability to power appliances meant for productive use of energy [32]. Furthermore, if and when the national grid does arrive, this microgrid can already serve as a ready distribution grid (otherwise, grid extensions are merely reduced to providing electricity to just the peripheries of villages, or the microgrids are left as stranded assets). Such bottom-up microgrids need to be an essential piece of the electrification puzzle, which not only complement other electrification pathways and efforts but also become a logical transition step from standalone systems, such as SHS. In this way, it also helps in preserving the sanctity of the SHS electrification pathway, which is already underway with remarkable momentum.

Please note that this is only one possible solution and by no means the silver bullet for attaining universal electrification. Nonetheless, given the current state of off-grid electrification, the massive investments in the off-grid sector and taking into account the inevitable climb up the electrification ladder, this seems to be the most promising route to scale electrification efforts.

6.2. Comparison of the Various Electrification Pathways

Table 2 presents a qualitative comparison of the electrification pathways presented in this article. The different aspects considered are in the context of universal electrification only. As discussed before and seen in Table 2, each of the three present-day electrification pathways have relative merits and demerits, while the decentralized SHS-based microgrids generally perform well across the different aspects of comparison. The scalability and adoption aspect deserves a special mention, as that is a particular pain-point in addressing the urgency of accelerated electrification. SHS can potentially continue with their current momentum in adoption, but the electricity access will still be limited, as discussed in Section 5. Interconnected SHS-based microgrids, on the other hand, can scale just as wide as SHS, but also grow in size due to interconnectivity.

Table 2. A qualitative comparison of the different electrification pathways on various aspects.

Aspect	SHS	Centralized Microgrids	Central Grid	Decentralized SHS-Based DC Microgrids
MTF tiers supported	Tier 2, sometimes tier 3 [36]	Tiers 1–5 possible, but fixed	Tiers 1–5, and on demand	Tiers 1–5, flexible [32]
Ease of electrification	Very high	Medium	Low	High [32]
Climbing the electrification ladder	Very low, only till tier 2/3 [36]	Low	High	High [32]
AC/DC	DC [16,40,42]	AC [50], DC [49,51] or hybrid	AC	DC [32]
Community loads/PUE	No	If planned, yes	Yes	Yes, depending on the microgrid size [32]
Scalability & adoption	Very high but limited to tier 2/3	Limited [49]	Limited [49]	High [32,49]

Another aspect where SHS lacks as an electrification pathway is the ease of climbing the electrification ladder. This is due to its inherently limited size, as already discussed in Section 5.1. Centralized microgrid also ranks low on this aspect because of the usually fixed capacity while implementation. Grid extension potentially scores high on this aspect, but suffers from the issue of 'energy demand mismatch' on the user side. Low electricity demand translates to financial disincentives for grid extension, as explained in Section 2. A decentralized SHS-based microgrid pathway, as seen in Table 2, ranks high on the aspect of climbing up the electricity ladder. This is because energy sharing through SHS interconnectivity can significantly lower the need for additional storage otherwise needed for standalone expansion, while still retaining the option of modular expansion of PV generation. Also, such a decentralized microgrid would also alleviate the problem of electricity demand mismatch on the user side, as the microgrid expansion can be 'on demand'.

7. Summary

The three different pathways for electrification, i.e., grid extension, centralized microgrids, and standalone solar-based solutions, such as SHS, each come with their own set of limitations. SHS is a promising solution so far in achieving up to tier 2 level electrification. However, in its current state, SHS can only light the way but is far from being the electrifying solution to achieve universal electrification. While decentralized solutions, such as pico-solar and SHS can provide on-demand electrification, the central grid can provide higher levels of power commensurate with tier 4 and tier 5. For climbing up the electrification ladder and enabling the use of high power appliances, an interconnected SHS-based DC microgrid can overcome many of the limitations of SHS as well as centralized microgrids. Such a bottom-up microgrid could well be the missing link between the present electrification pathways, forming an integral part of the universal electrification jigsaw.

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