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Chapter 6

# Off-grid Access to Electricity Innovation Challenge

“to develop systems that enable off-grid households and communities to access affordable and reliable renewable electricity”

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## The challenge of universal access to modern energy



There are currently 1.1 billion people globally living without access to electricity, 80% of whom live in rural areas, mainly in South Asia and Sub-Saharan Africa [1]. Hence the challenge of bringing stand-alone off-grid and/or mini-grid solutions to these populations is of paramount importance in fulfilling the United Nations' Sustainable Development Goal (SDG) no. 7, that is, to ensure access to affordable, reliable, sustainable and modern energy for all by 2030. The challenge is substantial since current projections indicate that almost 700 million people would still be without access to electricity in 2030, 90% of them residing in Sub-Saharan Africa [1]. In developing Asia and Latin America a nearly full rate of electrification is expected by 2030, with India being a big success story in having provided more than 500 million people with access to electricity since 2000 [1] its target being to achieve complete electrification by March 2019.

A major challenge in providing the remaining 1.1 billion with access to electricity is the fact that the vast majority lives in rural and remote areas far from the national grid. Furthermore, inhabitants of these areas often have low and irregular incomes, meaning that electrical power load densities in these areas are low. As a result, the combination of low levels of electricity consumption and difficult terrain makes

it costly as well as cumbersome to connect rural populations to the grid in a sustainable fashion. As a result, policy-makers and electrification strategies often give less emphasis to rural electrification than to electrifying urban centres and industrial areas.

Given this situation, the question to be answered is whether it is possible or reasonable to promote clever routes to the provision of access to these rural populations without having to rely on "classical" grid expansion. Possible combinations of novel technologies should be considered and be given an opportunity to prove their worth. It seems that, for these particular situations and geographical circumstances, the focus should rather be on solar-based technologies.

Indeed, access to electrical energy is not a binary between having access to electricity and not having it, as it is the case for utility-supported grid electricity [2]. With the recent diffusion of so-called 'pico solar' products (solar portable lights and solar lanterns with an effect below 10 Wp), solar home systems (SHS), and mini-grids to supplement or be used as alternatives to utility grid electricity, access to electricity should be measured in a graded fashion, i.e., according to the level and quality of the service provided. A systematic way of measuring and verifying access to electricity is provided by the Multi-Tier Framework, which distinguishes between five levels or tiers of energy access as illustrated in Table 1 [3].

**Table 1.** Different levels of electricity access defined by the Multi-Tier Framework [3] ("task lighting" refers to having access to lighting to be able to perform a limited number of important tasks like reading, cooking, etc.).

	TIER 0	TIER 1	TIER 2	TIER 3	TIER 4	TIER 5
Tier criteria		Task lighting AND phone charging	General lighting AND phone charging AND television AND fan (if needed)	Tier 2 AND any medium-power appliances	Tier 3 AND any high-power appliances	Tier 2 AND any very high-power appliances
Annual consumption levels, in kWhs		≥4.5	≥73	≥365	≥1,250	≥3,000
Daily consumption levels, in Whs		≥12	≥200	≥1,000	≥3,425	≥8,219

While many households experience a considerable improvement in being supplied with electric light and the opportunity to charge their mobile phones (tiers 1 & 2), other households might need electricity to run appliances for productive use and income-generating purposes (tiers 3 to 5) [4]. It is unlikely that all countries will be able to reach the highest tiers of access by 2030. Therefore, the Multi-Tier Framework is useful for countries and development agencies in devising policies according to context and funding opportunities, as well as to evaluate progress until the highest tier of access is reached.

## Technological trends

Fortunately, recent years have witnessed spectacular progress with solar-based off-grid electrification that has enabled millions of people to be given access to electricity through either pico solar products, SHS or various types of mini-grid, both AC and DC. This development has been aided by a combination of continuing uncertainty in the price of conventional energy sources<sup>1</sup> and drastically falling solar module prices. This has been the result of the increased efficiency of modules, cost reductions through economies of

<sup>1</sup> The global price of oil has increased steadily from 20-25 USD per barrel in the 1990s, reaching an average level of 100 USD per barrel for the period 2007-2015, after which the price has dropped again to around 60 USD per barrel <https://www.eia.gov/todayinenergy/detail.php?id=34372>

scale and increased competition, especially from Chinese manufacturers. Since 2010, average module prices have fallen by more than 80% and average annual global manufacturing capacity has increased by 30% [5]. Furthermore, the price of solar PV products has not only benefitted from the reduced manufacturing costs of panels, it has also been supported by an overall improvement in the efficiency and performance of complete systems [6; 7].

## Individual systems

Solar technology has reduced costs especially for individual systems, such as solar pico products and SHS, which are mainly used by residents of dispersed settlements, informal settlements and low energy density areas. For these systems, improvements have come from the use of small lithium-ion batteries, energy-efficient lighting alternatives (particularly Light Emitting Diodes or LEDs) and balance of system components (BOS), e.g. inverters, charge controllers, cables and wires. Thus, the price of an SHS offering lamps, a radio and a television dropped from 991 USD in 2009 to 354 USD in 2014 and is expected to decrease by another 50% by 2020 [7]. Pico solar products, which offer a few lights and allow households to charge their mobile phones, have likewise experienced significant falls in price. In 2010 a solar lantern cost around 20 USD, but by 2015 the price had dropped to a little more than 4 USD. Surveys from Kenya, Uganda and Tanzania indicate that households typically spend 36-73 USD for kerosene for lighting over the two-period that a solar lantern normally lasts [8]. Hence, significant savings for households are within reach by switching to solar-powered lighting. As a result, the sales of off-grid solar products has increased rapidly since 2012, reaching almost 31 million units sold cumulatively by the first half of 2017 [9]. Using solar PV-based technology to reach Tiers 1 and 2, which both offer electric light and phone charging, with the addition of a television or a fan respectively, has thus become considerably less costly over the past decade.

## Mini-grids

A mini-grid is a small electricity grid that connects villagers to an electricity-producing unit. It is a major building block in bringing electricity supplies to remote communities,<sup>2</sup> being a least-cost option for the provision of electricity to small towns and villages with adequate load densities wherever local resources make this possible. Mini-grids are reaching higher tiers of energy access that involve the use of medium- and high-power appliances such as refrigerators, water pumps and hair-dryers. Thus, mini-grids can supply sufficient electricity for productive purposes and can sustain income-generating activities in a way that pico solar and

SHSs cannot [11]. Mini-grids are in most cases intended to be connected to the main grid when consumption in the mini-grid reaches a level that makes it economically feasible to link a transmission line to the main grid. To ease future integration with the main grid, it is important for mini-grids to be constructed according to normal grid standards, though this may slightly increase the installation costs.

Electricity generation for mini-grids can come from diesel engines or renewable sources, possibly supplemented by electrical storage. Which technology is the least-cost option depends on the intensity and availability of renewable resources, as well as on the capacity of the mini-grid. As a rule of thumb, hydropower and wind are best suited for larger installations, biogas and thermal gasification for medium-size installations, while biofuels and solar PV are modular, making them feasible for the whole range of installations from small to large [12]. In general, small-scale hydro is a well-proven technology and the least-cost option [13]. In areas with constant and good wind conditions, wind turbines have proved to be a feasible option for larger installations in combination with diesel engines > 50 kW [14]. Small wind power in the size of 2-10 kW has been tested in many countries, but in only a few cases have they proved to be economically feasible compared to diesel-based solutions [15]. Biogas from animal manure and gas from biomass gasification have been tested in many countries. India has hosted a number of programmes for small-scale thermal gasification of biomass to supply mini-grids, but in spite of some isolated success stories, gasification of biomass for mini-grids has proved difficult [16]. Biogas programmes for rural electrification have been implemented in India and recently in a number of countries in Africa (Kenya, Ethiopia, Tanzania, Uganda and Burkina Faso) through a Dutch development programme. While use of gas for cooking has been a success, there are few reports regarding mini-grids supplied by electricity produced from biogas [17]. Mini-grids supplied by electricity from locally produced biofuel from *Jatropha* was tried out in many countries in 2006-2012, but currently very few of these installations are in operation due to the unexpectedly high production costs of *Jatropha* oil [18; 19; 20]. Solar PV has until recently produced electricity at a higher cost than diesel alternatives, but the solar technology is reliable, and in the Indian state of Chhattisgarh, 1,200 solar mini-grids (1-10 kW) have successfully been running for up to fifteen years [21]. Given the fallings cost of solar PV in the last few years, described above, this technology, combined with batteries, is likely to become the least-cost and preferred technology for mini-grids.

A recent major technological advance in the area of mini-grids is the ability to integrate renewable and non-renewable energy technologies with batteries – so-called hybrid mini-grids. This minimizes operating costs, even though invest-

<sup>2</sup> For a typography of mini-grids, see [10]

ment costs increase. The development and diffusion of hybrid mini-grids has to a large extent been driven by the low cost of solar PV, but also combinations of renewable technologies with different generation profiles throughout the day can be used to adapt production profile to load profile and thus reduce battery size. In this regard, successful experiments with solar, wind and gasifier hybrids were conducted in India in mid-2000, and integration of wind and reduction in battery size in PV systems are about to be demonstrated in a project being carried out in Kenya by DTU and a large Danish wind-turbine manufacturer.

To reduce costs and increase reliability, modern hybrid mini-grids have started to use smart grid features (see Chapter 5) to control intermittent production and load, internet-based systems for distant operation and control, and smart metering and mobile-based payment systems for financial management [22]. Experiences from mini-grids can therefore be used as the first steps in introducing smart grid features in existing grids, and in countries with a large number of mini-grids, this can be a test-field for modular networks [23].

While most mini-grids are 240 volt AC grids and therefore in most cases compatible with normal utility networks, a number of DC-based mini-grids still exist at 24 and 48 volts. The advantage of DC mini-grids is that capital expenditure to provide the same level of energy service can be reduced markedly. This makes DC-based micro-grids particularly relevant for low-income households since the connection fee is modest, resulting in a similarly low tariff [24]. In India and Pakistan, DC-based micro-grids are receiving a lot of attention, and very recently the Bureau of Indian Standards has published 48 volt DC standards for micro-grids. The same standards are now being discussed in the International Electrotechnical Commission for adoption as international standards.

Overall, the attractiveness of renewables, in particular solar, as an alternative to the provision of electricity from conventional energy sources has improved drastically over the past decade. Table 2 shows the distribution of solar PV installations across the different market segments from July 2015 to July 2016.

**TABLE 2.** The product-based market segmentation methodology applied in this article (for reference, the corresponding MTF energy access tier is indicated for each segment, as well as sales volumes per segment for July 2015–June 2016 [25]).

Market segment (solar PV capacity)	Service provided	Corresponding Mtf energy access tier	Volume of products sold in sub-Saharan Africa (July 2015–June 2016)
0-1.5 Wp	Single light only	Tier 0	2,178,836 (53%)
1.5-3 Wp	Single light + phone charging	Tier 1—Task lighting AND phone charging	1,161,280 (28%)
3-10 Wp	Multiple lights + phone charging		513,435 (12%)
11-20 Wp	Entry-level stand-alone solar system (3-4 lights, phone charging and low power appliances (e.g., radio, fan))		100,463 (2%)
21-49 Wp	Basic capacity stand-alone solar system (above plus power for TV & extended capacity)	Tier 2—General lighting AND phone charging AND television AND fan (if needed)	64,296 (2%)
50-100 Wp	Medium capacity stand-alone solar system (above but with extended capacity)		64,328 (2%)
100 Wp+	Higher capacity stand-alone solar system (above but with extended capacity)	Tier 2 (Large systems could qualify for Tier 3)	44,163 (1%)

## New business models

While the significant decrease in the price of solar PV technology has been a major driver for the spread of solar products for rural electrification, the process is further supported by the emergence of new and innovative business models by private-sector actors taking advantage of the digital revolution.

In general, four delivery models can be distinguished for individual households: retail, pay-as-you-go (PAYG, to be elaborated below), consumer financing and fee-for-service [25]. The retail model is the conventional approach, where-

by customers simply buy the products off the shelf through existing networks of distributors and retailers. The PAYG approach is a new and innovative model that takes advantage of the widespread use of mobile telephony and the breakthrough of smart metering. The consumer financing model is based on a partnership between a solar PV supplier and a financial institution (e.g. commercial bank, micro-finance institution etc.). The financial institution takes the responsibility for providing consumer finance and collecting repayments, while the supplier is relieved of the cash-flow burden. The fee-for-service model does not transfer ownership of systems to customers; rather, customers pay a fee for usage or recharging products. In general, the retail



and PAYG delivery models have proved efficient in reaching scale in mature markets, whereas the fee-for-service delivery model was mainly used at a time when PV solutions were still very costly, especially in countries such as Morocco and South Africa, where the utilities retained their monopolies [2; 4; 25].

While the vast majority of solar PV products are sold through the retail model, the PAYG model merits further elaboration since its innovative new approach allows suppliers to overcome some of the major challenges associated with bringing electrification to remote and low-income families in developing countries [26]. The PAYG approach avoids the high upfront costs of installing a whole system, as it allows consumers to pay it off gradually via their mobile phones, while smart metering enables suppliers to control the consumption of electricity remotely in cases where a consumer fails to pay. Combined, these innovations overcome the geographical barriers to having to collect payments. The flexibility to pay small amounts is particularly important, as it makes solar products a viable alternative to buying smaller amounts of kerosene or diesel oil for lighting.

Furthermore, after full repayment in 12 to 36 months, households will potentially be able to enjoy free electricity for the remaining lifetime of the system. Having installed pico solar or SHSs allows households to reduce the costs of access to electricity and charging their phones. Moreover, the fact that this solution provides lighting to consumers in the evening when they need it most is another valuable advantage, since rural consumers have been shown to have a high willingness to pay for basic lighting services [27]. However, one shortcoming of the PAYG approach seems to be that it mainly targets households in the 6-40 USD/day income range but does not reach households and consumers at the very bottom of the pyramid, who spend a large part of their income on lighting services [28].

One of the pioneers of the PAYG approach is the Kenyan company M-KOPA, which was founded in 2011 to take advantage of the mobile payment schemes that emerged in Kenya in 2007. M-KOPA sells SHSs to customers by charging a small deposit of roughly 30 USD and subsequently letting customers pay the equivalent of 0.5 USD per day over a period of twelve months to pay off and finally own the system. By 2017, the company had connected more than 500,000 households across Kenya, Tanzania and Uganda to affordable solar power. Several other companies applying more or the less same business model have now entered the market, including Mobisol, Azuri Technologies, Off-Grid Electric, Bboxx, Solar-Now and Simpa [6; 26].

Larger mini-grids for towns situated far from the grid are generally owned and operated by national utilities and dis-

tribution companies. However, since the deregulation of the electricity sector, a variety of publicly supported business models have been experimented with. In Sub-Saharan Africa, since the turn of the century electrification agencies have supported mini-grids under different business models. In Burkina Faso, about 180 mini-grids are owned and operated by village cooperatives, while another fifty are owned and operated by private companies in Mali. In both countries, mini-grids are subsidized, and tariffs are subject to approval by the regulatory authorities.<sup>3</sup>

In India, government agencies run around 2500 mini-grids, and in the last ten years more than 200 have been established by private operators [21]. Recently, also in SSA, new private business models for mini-grids are emerging in competition with the existing organisational arrangements run by the utilities. In Kenya, twenty mini-grids fully financed, owned and operated by private companies have been installed since 2012. By using smart metering and PAYG systems, they have been able to charge cost-reflective tariffs, which are five to ten times higher than regulated tariffs charged by utility grids. This has been possible because consumers find it cheaper than the alternatives, but as with the SHS, there are the same challenges of reaching the poorer segments of the population. Four companies in Kenya are currently following this approach and trying to negotiate access to the same amount of subsidies and cross-subsidies as mini-grids established by the rural electrification authority and the distribution company. One of the Kenyan companies has so far established ten mini-grids. It has up to a hundred systems in the pipeline, and is currently spreading its business to other SSA countries [22; 29].

## Public support

The improved cost competitiveness of solar PV and the emergence of new and innovative business models have been major drivers of the expansion of off-grid solar products and of small private PV-based mini-grids for rural electrification, but this progress would not have been achieved on the current scale without supportive public initiatives and programmes [4; 30].

For off-grid products, public support has been vital in the attempt to counter the large inflow of low-quality counterfeit solar products that are damaging the image of the industry as a whole. One particular initiative established by the World Bank's International Finance Corporation in 2010 under the name of 'Lighting Africa' has been very successful and is currently operating in eleven African countries. The initiative has been scaled up, now being called 'Lighting Global', and new programs have been launched in India, Bangladesh and other Asian countries. The initiative is

<sup>3</sup> For further details, see e.g. [4]

a global certification scheme for pico-scale solar products that aims to increase consumer confidence by ensuring a minimum level of product quality as well as transparent advertising. Furthermore, the initiative collects data that serve as valuable statistical information on the sales of certified products in Africa.

An example of a very successful public programme to support the uptake of solar PV products is the IDCOL Solar Home System Program that has been implemented in Bangladesh since 2003. IDCOL, the state-owned financial institution, implemented the program in collaboration with thirty partner organisations, whose main responsibility was to be locally present to promote and service the SHSs [21]. By May 2017, 4.1 million SHSs had been supplied to rural areas of Bangladesh through a consumer finance model in which the purchase of an SHS is financed by a repayment scheme consisting of 36 equal instalments.

In some countries such as Rwanda, Kenya, Nepal and Myanmar, the use of solar lanterns and SHSs is being incorporated explicitly into national rural electrification strategies. In particular, Kenya's Off-grid Solar Access Program is an example of an innovative public program offering financial incentives in the form of results-based finance and a debt facility for solar off-grid companies currently operating in more densely populated areas to expand operations to off-grid households in underserved counties [31].

Also, mini-grids need considerable amounts of donor finance or cross-subsidies from urban electricity consumers to meet the same tariff level as grid-connected electricity. In a number of countries rural electrification funds are being set up to provide subsidies to reduce the tariffs of private mini-grids and in mini-grids owned and operated by cooperatives. These funds are replenished by funding from international donors and from levies on electricity sold to urban consumers. In some countries, such as Kenya, similar legal frameworks are being introduced, but private companies are still not being given the same amount of subsidies as public entities [32].

## Remaining challenges

Among researchers and practitioners, there is a consensus that the least-cost option for achieving universal access is to be found in a combination of grid extension, mini-grids and off-grid solutions, and that challenges remain for all three approaches. Based on the literature [4; 21] and the authors' own experiences as researchers and consultants, we will conclude this chapter by highlighting the key challenges. These are:

- to ensure proper planning that delimits the geographical areas for grid-extension, mini-grids and off-grid solutions. Such plans have been elaborated in most countries,

often funded by international donors and carried out by researchers and international consultants: see e.g. [32; 33]. Among the challenges in this regard are that plans may overlap with one another, they may be funded by different donors with different perspectives, and the continued planning process may sow confusion over the status and legitimacy of existing and future plans. It is therefore important for governments to take the lead in the planning process and ensure the plans are followed up.

- to establish a forward-looking, consistent and stable policy and regulatory frameworks that define clear roles for private and institutional actors to become involved in rural electrification. This includes the existence of a strong and independent regulatory authority and a level playing field for public and private actors in terms of having access to subsidies and cross-subsidies, which are necessary to reduce tariffs for mini-grids to an affordable level.
- to ensure sufficient financing flows to mini-grid systems. The investment needed for mini-grids can to some extent be sourced through donor funding in the form of grants and loans or through cross-subsidies from high-consumption consumers in electrified areas. But to fill the investment gap, the big challenge is to attract large amounts of private capital, and especially to establish public-private partnerships to build mini-grids, while still ensuring affordable tariffs for the rural poor.
- to provide cheaper and higher tiers of energy access to rural households in dispersed settlements. Up to now the private sector has mostly been able to reach the lower tiers of energy access for the relatively wealthier part of the bottom of the pyramid. There is therefore still a challenge to achieve higher tiers of energy access for all income brackets, and to see how government and donor support can be integrated into these approaches to reduce costs for the lower income brackets.
- to build sufficient technical and organisational capacity to service target areas. Despite the technological breakthroughs described earlier, the remoteness and distributed nature of consumers living in rural areas require that technical and organisational capacity is available locally to reduce operational and maintenance costs.

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