COMPATIBILITY AND INTEROPERABILITY

TECHNOLOGY ROADMAP

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EFFICIENCY FOR ACCESS COALITION

Acknowledgements

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Acronyms and Abbreviations

AC	Alternating current
DC	Direct current
DFI	Development Finance Institutions
EST	Energy Savings Trust
FI	Financial Institution
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IOT	Internet of Things
LEIA	Low Energy Inclusive Appliances
MPPT	Maximum Power Point Tracking
NGO	Non-Governmental Organization
PAYG	Pay-As-You-Go
PnP	Plug-and-Play
PV	Photovoltaic
R&D	Research and Development
RF	Radio Frequency
SDG	Sustainable Development Goal
SHS	Solar Home System
TWG	Technical Working Group

Executive Summary

1.1 Introduction

Context for This Roadmap

The Efficiency for Access Coalition brings together fourteen organizations focused on initiatives to drive market scale in near-to-market weak-and off-grid appliance products, support innovation in horizon appliance technologies further from low income markets, and improve information and co-ordination among development sector and industry partners. In an effort to accelerate the global market for highly energy-efficient appliances, Efficiency for Access introduced a new research and innovation program in early 2017 with the goal to double the efficiency and halve the cost of a suite of appliances that are well-suited for energy access contexts. The Low-Energy Inclusive Appliances (LEIA) program, funded by UK aid, seeks to accelerate the availability, affordability, efficiency and performance of a range of appliances and related technologies suited to developing country contexts.

Two previous LEIA roadmaps, one on solar water pumps and one on refrigeration, identified pathways for improvement of specific appliance technologies. This LEIA roadmap is the first to focus on general enabling technologies for the off-grid industry. Compatibility and interoperability, which refer to the ability of systems and components to work together in the same environment, including the exchange of information, are key features of mature markets for a variety of technologies around the world. Though most off-grid companies are not focused on these topics today, they will become increasingly important as the off-grid market matures. This roadmap should be viewed as a first step towards defining the requirements for that future mature off-grid industry.

Compatibility and Interoperability in the Off-Grid Context

A key challenge to growth in any early stage market is commoditization. Custom solutions work well when companies have markets to themselves, but when markets grow, custom solutions become a barrier to market efficiency. Limiting consumer choice to custom products may make sense from a particular system provider's perspective, but incompatibility between systems locks consumers into a product regardless of its merits relative to the competition. This tends to discourage market growth, which is, in the off-grid context, antithetical to the goals of policymakers, DFIs, and others striving to achieve the United Nations Sustainable Development Goal (SDG) 7.1 of ensuring universal access to affordable, reliable and modern energy services by 2030.

For independent appliance manufacturers, customization of their products for different system providers adds to manufacturing costs. In addition to higher cost, market efficiency is decreased if consumers' ability to buy or sell appliances is limited by a lack of compatibility with systems used by other consumers. This situation would be expected to worsen as off-grid solutions expand in line with SDG7 goals, meaning that custom systems may sit together in close geographic proximity. The natural tendency in such a circumstance would be for a secondary market for appliances to emerge, but this would be inhibited by a lack of compatibility. This could result in a circumstance similar to the one affecting incompatible AC adapters that has led to tens of thousands of tons of electronic waste in the EU alone.

From the system provider and appliance manufacturer standpoint, there are considerable risks associated with commoditization of the market. Besides the potential impact on profitability, a lack of guarantees of compatibility and interoperability make it difficult to ensure predictable behavior of a system with an unknown appliance added to it. System providers thus face the additional pressure of keeping their systems from being damaged and the consumers who use them safe. This implies that there needs to not only be a focus on compatibility and interoperability, but on appropriate labels and consumer education so that consumers are aware when systems are compliant.

Given the business risk associated with commoditization of the off-grid market, it is understandable that compatibility and interoperability are low on the priority list for SHS and minigrid companies today. This is not unusual for emerging technologies and presents a challenge for roadmapping efforts, which can only be successful with sufficient input from relevant market players. However, the perils of not addressing these issues at a relatively early stage of market development are evident in the history of many technologies in which seemingly dominant market players are unable to adapt to market trends in favor of incompatible technologies and fall by the wayside as a result.

Background on Roadmaps

Roadmaps are best seen as part of a planning process in which creation of the roadmap is as important as the roadmap itself, because the roadmapping process helps to develop, organize, and present information about critical product requirements and performance targets that must be met in certain time frames. Roadmaps identify the technologies needed to meet those targets and provide information necessary to make trade-offs between technology alternatives. Roadmaps normally include some level of technology development or R&D, either internal to a company or via external partnerships.

A roadmap that depends on industry cooperation exposes the tension between cooperation and competitiveness inherent in the roadmapping process. To have a larger impact on the market, companies must be willing to cooperate on a pre-competitive basis, working together to identify common customer needs and technology strategies. Though some companies may be wary of sacrificing competitive advantage by cooperating this way, combining resources can avoid redundant funding of research and drive greater market pull, thereby resulting in the availability of technologies that no single company could develop on its own.

This Roadmap

To the extent that compatibility and interoperability of off-grid systems could be achieved through industry consensus involving existing technologies, traditional roadmapping would not normally apply. However, because some new technologies may also be needed to achieve compatibility and interoperability goals, a roadmap may be useful in identifying R&D gaps in addition to highlighting where industry coordination is needed.

This roadmap was prepared with input from a Technical Working Group (TWG) made up of representatives from SHS companies, PAYG software providers, appliance manufacturers, an industry association, NGOs, and standards organizations. Given the early stage of market development in the off-grid sector, it is not possible to state numerical targets and timelines for achieving them with specificity as one might do in a more mature market. Nor is it possible at his stage to make definitive recommendations on technology alternatives to be considered. However, this document can serve as a starting point that can help drive progress as the off-grid market continues its rapid growth.

1.2 Scope and Structure of the Roadmap

A roadmap scoping document was prepared by the TWG, with the goal of defining the boundaries of the roadmapping effort in terms of products and critical functionality of the systems and appliances being considered. TWG discussions were informed by the DC Local Power Distribution (LPD) approach described by Nordman & Christenson and shown in Figure 1.

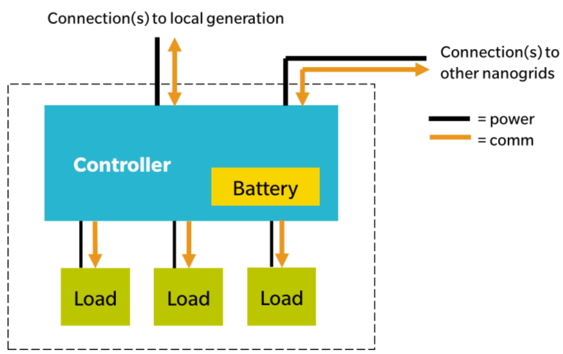

Figure 1: Schematic of local power distribution, termed nanogrid in the figure, but applicable to SHSs. (Nordman & Christenson, 2015)

A controller connects to local generation and to loads, as well as to other systems (described as nanogrids in the figure). Applying the figure to a SHS, local generation would be from the solar panel and the controller would contain a battery, as shown, but would also include other hardware such as a charge controller. Loads would be lights, phone charging, and any appliances used with the system.

Currently, SHSs are very seldom connected to each other in a pooled configuration, but there are existing companies that implement this approach in adjacent buildings. The application of this figure to minigrids is straightforward as well, except the local generation would be centralized rather than distributed and the systems would usually not include a battery.

The communication component is a unique feature relative to most current off-grid systems. With appropriate protocols, loads could be managed by the controller consistent with preprogrammed power management protocols and/or a user interface. The controller could also manage power from adjacent systems or a minigrid. Other features that could be implemented in off-grid systems are a PAYG and/or user interface for system control and a communication interface for external system monitoring.

In considering the system and features described above, the TWG agreed on a set of relevant products (DC appliances, power supply controllers, plugs and cables) as well as a set of critical requirements for them. These include obvious electrical safety and compatibility requirements like using standardized plug types that are not interchangeable with plugs connected to incompatible supplies or loads, and cables that are sufficient for power distribution and appliance loads. More advanced requirements include: appliances that can communicate their power needs and operational status to the controller; controllers that can manage power based on that communication; controllers and appliances that can communicate their operational status to a user and/or distributor, repair center, or manufacturer and allow for functional control; and controllers and appliances that can comply with a standardized PAYG management platform.

Having defined the scope of the roadmap from the standpoint of products and functionality, the desired functionality was divided into the following technology areas: electrical connectivity; power distribution connectivity and communication; general data communication; PAYG data communication; and low cost embedded controllers or other hardware necessary to support these functionalities. The drivers in each of these technology areas were then identified.

1.3 Compatibility and Interoperability Technology Drivers

Electrical Connectivity and Compatibility

Despite more than a hundred years of electricity system development, it was not until 1986 that international standards for AC plugs and sockets were agreed. However, only two countries have adopted these standards and instead there are currently 14 main plug/socket types that do not uniquely correspond to the 8 voltages and 2 frequencies in use around the world. As a result, AC appliances must conform to different national standards corresponding to their target markets.

Avoiding this outcome should be a central goal of all stakeholders in off-grid markets. However, for DC SHSs and appliances, existing usage is governed largely by the convention of particular off-grid system providers rather than by any standards framework. In fact, no system for tracking what types of connectors are used by which providers is in place and the only data is from limited surveys. Ideally, standardization of electrical connections would include a range of design voltages, including mobile phone charging at 5 V, 12 V for many off-grid appliances, and varying voltages for LED lights. It is not yet clear what voltages will be most prevalent in the design of higher power off-grid appliances.

In addition to the concern about connectors, systems must include cables that are appropriately sized for the current required by the devices connected to it, and must manage any voltage drops associated with long cable runs. If a system is plug and play or integrated by a third party, appropriate cables may be provided with it. If, however, appliances are sold separately and are to be added to systems by a consumer, appliance manufacturers may need to provide appropriate cables and consumer education.

An important safety focus for off-grid system compatibility is to avoid harm to the user or damage to the appliance or the controller by ensuring voltage compatibility and sufficient current carrying capacity of connectors, cables, and components, even if a plug and socket match. This could be addressed through standardized connections or a labelling system that would warn users of incompatibility. Another approach would be to overspecify the system by standardizing at a higher voltage and current capacity, but this would add to costs because of more expensive components.

Another important focus is to ensure sufficiency of supply, which is more challenging to address and places a greater burden on consumers. A user connecting excessive load on a low capacity minigrid or SHS may trigger a fault or rapidly exhaust the available energy supply. One approach to the supply sufficiency problem would be to develop labelling schemes to indicate general appliance load/system sizing compatibility. This would require considerable consumer education to ensure the labelling system was understood and employed appropriately. A full solution would require active communication between load and supply, which could go beyond sufficiency of supply and include real-time power management.

Connectivity and Communication for Power Management

Passive approaches to electrical compatibility include proposals to have bar code labels placed on SHS or appliance connectors or on the devices themselves. These would contain information on the voltage and current limits associated with their use. A consumer could then scan the connectors or devices with a mobile phone and an application would determine their compatibility. Another approach along these lines would be to include LEDs in connectors that would indicate voltage or current incompatibility, but these have the disadvantage of requiring the connection to be made first.

Though valuable for equipment selection and compatibility checks, the limitations of passive approaches become apparent when one thinks about systems in actual operation, with seasonal variation in insolation for charging solar PV systems as well as systems that may be powering multiple loads. It would be desirable to have available a more active power management approach, preferably with a degree of user control. Active power management of appliances connected to a controller implies that the controller is able to selectively reduce the power consumption of loads connected to its ports. For lighting and some other appliances, this may not actually require communication, but with multiple appliances or in a distributed SHS or minigrid configuration, communication is required.

One immediate consideration for power management communication is what kind of interface could be used between appliances and the control box. Wireless interfaces are typically more expensive than wired connections. Wired connections could take a number of forms, depending on the communication protocol, interface, and associated microcontroller used. This again introduces the problem of plug and socket compatibility for these connections. One possibility is for power management functionality to be combined with a user interface or PAYG control functionality. In this case, solving the interface problem could create a path for multiple functionalities.

Another concern with power management is enabling the customer to choose which loads to cut back or shed. At any given time, a user may wish to prioritize maintaining temperature control in a refrigerator or ensuring that a television program is not cut off. This functionality could be implemented via a user interface on the control box, but could also be implemented via IoT functionality on a mobile phone.

Connectivity and Communication for Controller Interface

In many parts of the world, people live in family compounds with multiple buildings. SHSs installed in separate buildings could pool resources via power sharing protocols. It may be more likely that DC power sharing approaches are implemented first in grid-connected environments on university campuses or between corporate buildings. However, the technologies used in these contexts will probably be too expensive for off-grid applications. Developing an off-grid DC power sharing approach may be an R&D opportunity.

There are also millions of consumers who have access to weak or unreliable grids who would benefit from SHSs. In other cases, the main grid may arrive, meaning consumers (and system providers) may still want to get value from their existing systems. Connections between DC systems and AC power are more complicated, and will depend on whether consumers have adopted DC or AC appliances. Controllers that include rectifiers or inverters to adjust between AC and DC supply would be needed to keep power available to those appliances, whether from an AC main grid or minigrid, or a DC SHS or minigrid. Systems could also be split, with AC appliances connected to the main grid and lighting and phone charging on the SHS side for times during which the main grid is unavailable.

Most SHS systems would be too small to be taken up as distributed generation by a local utility, but this would ideally be the case for larger systems or minigrids. Inverters to enable that functionality are in widespread use in residential solar PV installations around the world. However, the inverters used for these connections must meet certain standards in order to support power quality and grid reliability. In the off-grid context, the amount of power supplied to the grid will be smaller and price sensitivity more acute, so inexpensive inverters with reduced functionality may be desirable. This is an area for potential R&D work.

General Data Communication/Internet of Things

Given the remote locations of many off-grid installations, there is a lack of ready access to repairs and maintenance. Remote monitoring of appliance performance may provide appliance manufacturers, distributors, or repair centers information about poor performance or failures without the consumer needing to report them. Similarly, it may be desirable to monitor the health and performance of a SHS to see if there are problems at the system level.

Some SHS providers that include PAYG build system performance monitoring into their PAYG functionality. However, a generally applicable, widely accepted protocol for system and appliance monitoring would be beneficial to aid in widespread adoption. A protocol could be designed to report on a comprehensive enough set of parameters for the most sophisticated systems, but actual implementation could rely on passing only a subset of the parameters for systems that need less. It would be necessary to define the parameters to be monitored, the protocol to be used, and the interface for the communication. Different data collection schemes would be required for areas with and without access to a mobile network.

User control of appliances via an interface would be desirable to enable control over prioritization of services. Generalizing user control to an application accessible by mobile phone would bring this capability into a category of functionality often identified as the Internet of Things (IoT). However, given fragmentation of IoT implementations in mature markets, that term as commonly understood is not particularly helpful in the off-grid context. It is probably most appropriate for the off-grid sector to develop low-cost, dedicated solutions that can be broadly replicated. Such solutions could be built around system monitoring or PAYG communication technologies and interfaces to reduce costs and complexity.

Interoperable PAYG Protocol

A SHS with PAYG is typically a packaged, plug and play system with lighting and sometimes appliances included. The appliances are owned by the company that manufactures and distributes the systems, sometimes with the intent of transferring ownership to the consumer via the PAYG contract or sometimes with ownership retained by the company. In either case, the security of the appliance is critical to the transaction.

Ensuring that an appliance included in a PAYG system is secured involves customizing the appliance for use with that system's PAYG platform, which can be unique to the company or one of several available third-party implementations. The appliance is locked out to prevent functioning unless it receives a correct code. This may involve the user entering a code via keypad or on their phone, or receipt of a signal directly by the controller via a mobile network. In any case, the appliance itself must have an interface and a microcontroller if it is to be secured to work only when authorized. It is challenging for an appliance manufacturer to implement multiple PAYG solutions for a single product and no doubt adds to product costs in a very cost-sensitive market. As a result, an interoperable solution that would allow multiple PAYG platforms to work with a single appliance would be highly desirable.

To date, PAYG operations have been focused on repayment for bundled systems, so the focus on the appliance has been limited to its securitization as part of the bundle, rather than accounting separately for appliance operation and payback. This could change in the event that more expensive appliances are sold under their own, separate PAYG contracts. Similarly, IoT applications could be written for control of specific appliances. Joint PAYG and IoT solutions that could be used at both the appliance and system levels would greatly simplify implementation costs for appliance manufacturers.

Existing third party PAYG companies should ideally participate in the process of developing an interoperable protocol to ensure that assets are secured sufficiently for their needs and that they are able to maintain the key backend features of their business that are most important to them: payment mechanisms and data related to their customer base. The goal would be to standardize the front-end interface and protocol to improve market efficiency while allowing companies to differentiate themselves based on their backend financial and customer relationship management solutions.

The Efficiency for Access Research and Development Fund was launched in November 2018. One of the winners of the first round of funding awards was Solaris Offgrid, which is undertaking a project called "open source standardized Pay-As-You-Go communication protocol." The first review and discussion of their proposal took place in May 2019, with work currently proceeding.

Low Cost Embedded Controllers and Other Components

A longer-term objective arising from interoperability in the off-grid sector is increased purchasing power and ultimately lower costs for system components, since standardized solutions lead to larger volumes which lead to decreased costs. The solutions identified in this roadmap could enable wider scale purchasing of key interface components, including microcontrollers designed to enable those solutions. Because achieving cost reductions depends on the development of widely adopted solutions, a focus on this topic necessarily comes after agreement on those solutions.

1.4 Summary and Next Steps

Because ensuring the compatibility of existing off-grid technologies through industry-wide agreement is typically something accomplished through creation of standards rather than a roadmap, this report recommends that the off-grid industry should identify companies willing to lead and/or participate in working groups focused on:

- Defining uniform requirements for electrical connectivity
- Deciding on approaches to connectivity in support of load management in SHSs, which might be accomplished though industry consensus but might also lead to specifying R&D activities to improve the available options
- Informing and supporting the R&D activities specified below

Based on the technology drivers identified in this roadmap, the recommendation for R&D activities (not in priority order) is:

- Development of power distribution connectivity interfaces and protocols to support load management in solar home systems, depending on industry consensus around whether such R&D is necessary
- Development of power distribution connectivity interfaces and protocols to support the ability of SHS controllers to interface with other SHS systems, DC minigrids, or AC minigrids
- Development of general data connectivity and communications interfaces and protocols for remote monitoring of systems and appliances
- Development of interfaces and protocols for an interoperable PAYG solution for controllers and appliances

The final technology area identified in the roadmap, low cost embedded controllers and other components for implementation of the communication protocols listed above, should be pursued after sufficient progress is made to support an industry consensus on the bulk purchasing requirements necessary to enable lower cost.

1.0 Introduction

Background

Efficiency for Access Coalition

The Efficiency for Access Coalition began in 2015 as a yearlong collaborative effort led by Global LEAP and Sustainable Energy for All, working to harness the power of energy efficiency to accelerate universal access to modern energy services. Today, this coalition brings together fourteen organizations, representing initiatives and programs spanning three continents, 26 countries, and 19 key technologies. These initiatives are focused on driving market scale in near-to-market weak- and off-grid appliance products, supporting innovation in horizon appliance technologies further from low income markets, and improving information and co-ordination among development sector and industry partners.

The Efficiency for Access Coalition is coordinated by CLASP, the leading international voice and resource for appliance energy efficiency policies and market acceleration initiatives, working alongside the UK's Energy Saving Trust (EST), which specializes in energy efficiency product verification, data and insight, advice and research. This coalition aims to achieve faster, higher-impact results by strengthening the coherence of support programs aligned with the needs of consumers and the market, based on a range of consumer research and industry consultation mechanisms.

Low Energy Inclusive Appliances (LEIA) Program

In an effort to accelerate the global market for highly energy-efficient appliances, Efficiency for Access introduced a new research and innovation program in early 2017 with the goal to double the efficiency and halve the cost of a suite of appliances that are well-suited for energy access contexts. The Low-Energy Inclusive Appliances program, funded by UK aid, will provide £18 million over five years to accelerate the availability, affordability, efficiency and performance of a range of appliances and related technologies suited to developing country contexts. LEIA was designed with extensive industry consultation regarding the specific challenges and opportunities of the off-grid clean energy access appliance market.

Meaning of Compatibility and Interoperability

Compatibility concerns the ability of two or more systems or components to perform their required functions while sharing the same hardware or software environment.[1] The components are compatible with each other as long as both can run (or simply reside) in the environment without adversely affecting the behavior of the other. The two components do not need to communicate with each other and can perform completely separate functions. Compatibility implies that there will be no unintended interactions that disrupt normal operation.

In the context of electrical devices, compatibility is the ability of a device to be connected to a power source and have the device function without adversely affecting the power source or other devices connected to it, beyond normal behavior like battery discharge. This relies in turn on socket, plug, and electrical compatibility. Compatibility is typically guaranteed by formal or de facto technical standards, with the former being agreed by national or international standards organizations and the latter created by tradition of use associated with market consolidation.

Interoperability extends the definition of compatibility to include the ability to exchange and use information. Interoperability is concerned with the ability of systems to communicate and requires that the communicated information can be understood by the receiving system. Interoperability relies on both hardware compatibility and communications protocols that may be governed by technical standards.[1]

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[1] The distinction between compatibility and interoperability may not always seem clear. For example, some devices used in solar PV systems may vary their function based on electrical inputs rather than explicit communication, e.g. a grid-tie inverter that varies its power output in response to frequency variations, or a maximum power point tracker that varies the impedance seen by a solar cell depending on operating conditions. These devices vary their behavior, but not in response to communication via a protocol that must be known to the system, and thus would be evaluated for system compatibility rather than interoperability.

Compatibility and Interoperability in the Off-grid Context

To understand the relative importance of compatibility and interoperability in the off-grid sector, it is important to define the systems and products being considered, as well as to understand the trends and market forces shaping them. Compatibility and interoperability are considerations that don't apply to the majority of products that have been sold in the off-grid sector to date, and how relevant they will be in the future depends on market forces and evolution.

Scope of the Report

For the purposes of this report, the term "off-grid" refers to solar home systems (SHSs) or stand-alone minigrid systems that are not connected to the domestic power grid (mains electricity). These are distinct from pico-solar products that offer integrated lanterns or multi-light systems, sometimes with mobile phone charging, under 10-12 Wp. These devices are typically fully integrated and not designed to connect to additional devices or appliances, so generally compatibility and interoperability do not apply to them.

It is important to note, however, that most of the market to date has been focused on these pico-solar products. The Lighting Global 2018 Off-Grid Solar Market Report[2] estimates that pico-solar systems represent 86% of the more than 130 million cumulative off-grid solar devices sold between 2010 and 2017, so this has been a highly visible and important market segment. But the relative share of pico system sales is decreasing as consumer demand for the greater energy services provided by higher power systems increases. There is also increased focus by policymakers, aid organizations, development finance institutions (DFIs), philanthropies and others on providing higher levels of energy services, as embodied in the target of the United Nations Sustainable Development Goal 7.1, to ensure universal access to affordable, reliable and modern energy services by 2030.[3]

Discussions of levels of energy service provision frequently reference the ESMAP Multi-Tier Framework,[4] a commonly used means of describing levels of access, shown in the table on the next page. The service tiers correlate with the power supplied by the system and therefore the types of devices used to provide the services. Though Tier 1 service could be provided by a small minigrid or solar home system, it is most frequently associated with pico-solar devices. This report is therefore focused mainly on Tier 2 and above, a rapidly evolving portion of the market made up of several different types of systems, appliances, and business structures.

Multi-tier Matrix for Measuring Access to Household Electricity Supply

ATTRIBUTES		TIER 0	TIER 1	TIER 2	TIER 3	TIER 4	TIER 5
1. Peak Capacity	Power capacity ratings[27] (in W or daily Wh)		Min 3 W	Min 50 W	Min 200 W	Min 800 W	Min 2 kW
			Min 12 Wh	Min 200 Wh	Min 1.0 kWh	Min 3.4 kWh	Min 8.2 kWh
	OR Services		Lighting of 1,000 lmhr/ day	Electrical lighting, air circulation, television, and phone charging are possible			
2. Availability (Duration)	Hours per day		Min 4 hrs	Min 4 hrs	Min 8 hrs	Min 16 hrs	Min 23 hrs
	Hours per evening		Min 1 hr	Min 2 hrs	Min 3 hrs	Min 4 hrs	Min 4 hrs
3. Reliability						Max 14 disruptions per week	Max 3 disruptions per week of total duration <2 hrs

Multi-tier Matrix for Measuring Access to Household Electricity Services

	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

Figure 2: The ESMAP Multi-Tier Framework. (World Bank, 2015)

Market Trends and Segmentation

Figure 3 highlights the rapid growth of the off-grid sector by showing estimates of the number of people served by various renewable energy technologies in different regions over time. Growth in the off-grid market is being driven by decreasing costs relative to grid extension, coupled with the realization by governments that off-grid electrification is a viable means of providing energy services. The International Energy Agency reports that 5 million people per year have gained access this way since 2012, compared to 1 million per year between 2000 and 2012.[5]

Solar-based technologies have expanded most rapidly, driven by cost declines in solar photovoltaics, though the pico segment (labeled "solar lights" in the figure) has dominated. Looking beyond the pico segment, SHSs serve the next largest share of the population, followed my minigrids. Projections of market growth show that minigrids are expected to play a larger role in energy access scenarios.[6]

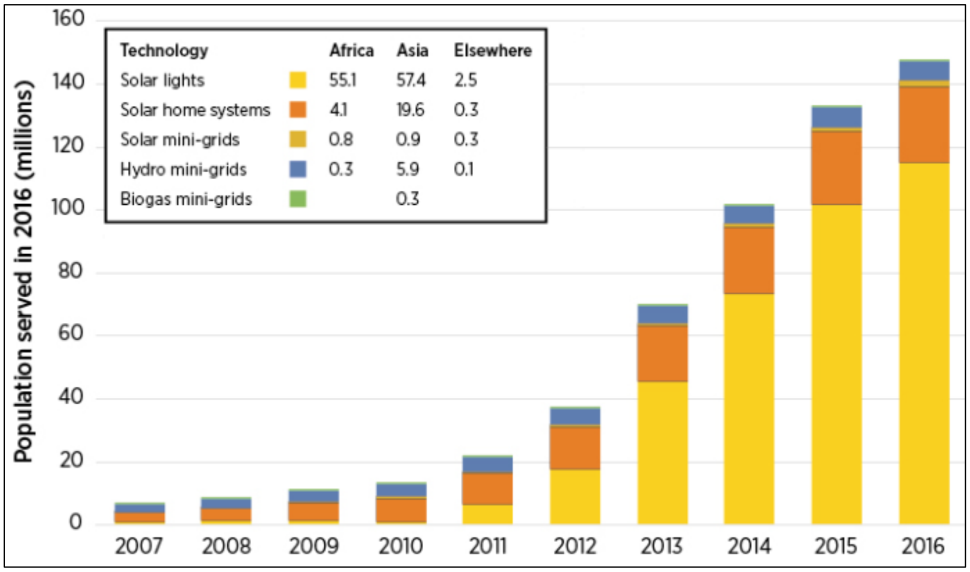


Figure 3: The number of off-grid renewable energy users served by system type (International Renewable Energy Agency, 2018)

The Global Off-Grid Lighting Association (GOGLA) divides the SHS segment into Plug-and-Play (PnP) and component-based systems.[7] PnP systems have all their components pre-packaged while component-based systems are compiled independently. Component-based systems put together via institutional subsidy programs, such as Bangladesh's Infrastructure Development Company Limited or India's National Solar Mission, must follow national specifications for component and system performance.[8, 9] Those put together by consumers or retailers, however, are not subject to such specifications, though retailers may follow local electrical code. Open-market or institutional component-based system suppliers are estimated by Lighting Global to have sold a cumulative 17 million units, with plug-and-play suppliers selling 2 million units.

Despite the diversity of electrification approaches and the relatively small size of the PnP market, it is the category that has received the most attention recently. This has been driven by the emergence of the PnP pay-as-you-go (PAYG or PAYGO) market, in which the purchase or rental of the system is enabled by mobile payments. This market segment grew at an average annual rate of around 140% between 2013 and 2016, starting from a small base. This growth has been concentrated in East Africa, due to the presence of strong mobile money ecosystems. The Solar Market Report estimates that total revenue growth for this segment will eclipse pico segment revenue in three to five years, and states that "[m]ost suppliers in the industry believe that nearly all future SHS system growth will be driven by PAYGO systems, barring markets such as India where PAYGO growth is likely to be contingent upon mobile money and other digital forms of payment taking off."

Market Challenges and Opportunities: The Role of Compatibility and Interoperability

A key challenge to market growth that will eventually be faced by both PAYG and component-based system providers is commoditization – the process whereby similar products become relatively indistinguishable from one another. Custom solutions work well when companies have markets to themselves, but when markets grow, custom solutions become a barrier to market efficiency. Limiting consumer choice to custom products may make sense from a particular system provider's perspective, but incompatibility between systems locks consumers into a product regardless of its merits relative to the competition. This tends to discourage market growth, which is antithetical to the goals of policymakers, DFIs, and others striving to achieve SDG7.

Because commoditization increases competition and tends to reduce profitability, the natural tendency is for companies to try to delay it as long as possible by bundling systems with more features. In the off-grid sector, this largely means adding more appliances. This is most cost-effective for a vertically integrated system provider, that is, one that manufactures its own appliances. However, for independent appliance manufacturers supplying products to multiple system providers, customization of their products for particular systems adds to appliance manufacturing costs. Appliance manufacturers thus have a higher stake in compatibility and interoperability than system providers.

In addition to higher cost, market efficiency is decreased if consumers' ability to buy or sell appliances is limited by a lack of compatibility with systems used by other consumers. This situation would be expected to worsen as off-grid solutions expand in line with SDG7 goals, meaning that custom systems may sit together in close geographic proximity, and consumers may wish to buy and sell appliances from each other. A lack of markets for used appliances could also lead to increased electronic waste as incompatible devices are discarded (see discussion in the Electrical Connectivity for AC Appliances Section about the waste problem from incompatible AC power adapters).

Another consideration for PAYG companies that bundle appliances is that they bear heavier debt burdens if appliances are included in the PAYG contract. These burdens will only increase as companies try to provide higher levels of energy services by including more appliance offerings. This adds to the complex investment picture for PAYG companies, which are already hybrid system provider and finance companies.[10] One solution may be for appliances to be "unbundled" and financed separately, perhaps through dedicated finance facilities, or marketed with their own, separate, PAYG contracts, which would require that PAYG functionality be included in appliances.

The linkage to the policy goal of expanding energy access exacerbates the natural tension between customization and commoditization that already exists in the market. From the policy perspective, compatibility and interoperability would seem to be key to enabling commoditization and scaling the market. However, from the system provider and appliance manufacturer standpoint, there are considerable risks. Besides the potential impact on profitability, a lack of guarantees of compatibility and interoperability make it difficult to ensure predictable behavior of a system with an unknown appliance added to it. Thus, besides the competitive pressure to maintain customized solutions, system providers face pressure to keep their systems from being damaged and the consumers who use them safe. This implies that there needs to not only be a focus on compatibility and interoperability, but on appropriate labels and consumer education so that consumers are aware when systems are compliant.

Given the business risk associated with commoditization of the off-grid market, it is understandable that compatibility and interoperability are low on the priority list for SHS and minigrid companies today. This is not unusual for emerging technologies and presents a challenge for roadmapping efforts, which can only be successful with sufficient input from relevant market players. However, the perils of not addressing these issues at a relatively early stage of market development are evident for many technologies, as some may recall from the videotape and optical disk format wars.[11, 12] Most relevant to this sector is the history of on-grid electrification, discussed in 0.

Technology Roadmapping for Compatibility and Interoperability

Before structuring a roadmap around compatibility and interoperability, it is useful to consider some background on the roadmapping process and how roadmaps are used in practice. To the extent that compatibility and interoperability of off-grid systems could be achieved through industry consensus involving existing technologies, traditional roadmapping would not normally apply. However, because some new technologies may also be needed, a roadmap may serve a useful role in identifying R&D gaps as well as highlighting where industry coordination is needed.

Background on Roadmaps

The term "technology roadmap" can refer to a range of efforts, depending on market or technology focus and the number and type of stakeholders included. In general, roadmaps are tools to accelerate the transfer of technology into products by improving the coordination of activities and resources in complex and uncertain environments.[13] The most common roadmap type focuses on market needs and seeks to provide critical linkages between business requirements and technology investment decisions needed to meet those requirements.[14]

Roadmaps are best seen as part of a planning process in which creation of the roadmap is as important as the roadmap itself, because the roadmapping process helps to develop, organize, and present information about critical product requirements and performance targets that must be met in certain time frames.[15] Roadmaps identify the technologies needed to meet those targets and provide information necessary to make trade-offs between technology alternatives.

Product roadmaps are the most narrowly focused and are often used by individual companies to align their internal resources around developing a new product. A roadmap with broader scope includes some level of technology development or R&D, either internal to a company or via external partnerships. At the broadest level, an industry roadmap is used by multiple companies (sometimes with government support) to inform R&D strategies and collaborative projects.[16,17] The table on the next page illustrates the trade-off between impact and participation for different roadmap types.

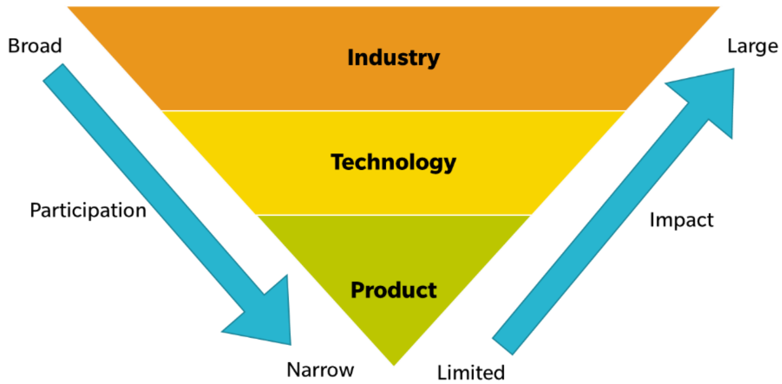


Figure 4: Types of roadmaps, with trade-offs between impact and participation. Adapted from (Emerging Industries Section, Department of Industry, Science and Resources, 2001)

One important feature of industry roadmaps is the tension between cooperation and competitiveness inherent in the roadmapping process. To have a larger impact on the market, companies must be willing to cooperate on a pre-competitive basis, working together to identify common customer needs and technology strategies. Including stakeholders up and down the value chain helps to provide the full picture of markets, products, technologies, and research. Though companies that are more vertically integrated or which have well-established customer and supplier relationships may be wary of sacrificing competitive advantage by cooperating this way, combining resources can avoid redundant funding of research and drive greater market pull, thereby resulting in the availability of technologies that no single company could develop on its own.

Roadmap Application to Compatibility and Interoperability

Ensuring the compatibility of existing technologies through industry-wide agreement is typically something accomplished through creation of standards rather than a roadmap, though it can be a less formal process than standard-setting, at least in the early stages. Often a company or group of companies will decide to work together to agree on a common approach. A well-known example of this in the connector space is the USB Implementers Forum,[18] an organization formed in 1995 to develop and maintain USB as a universal interface to replace the numerous connectors used in personal computers. The group was founded by seven companies which subsequently incorporated the interface into their products, driving proliferation in the marketplace. It now features more than 1000 members.[19]

Though this process is similar to roadmapping insofar as it involves industry collaboration, it is not a technology roadmapping activity unless it involves development of new technology to achieve the compatibility objective. The discussion of plug and socket compatibility in the Ofor example, is very important for off-grid market development but would not normally be appropriate for inclusion in a technology R&D roadmap. However, plug and socket compatibility is closely related to interoperability topics like power management, remote monitoring, and PAYG operations. Depending on how those technologies are implemented, plug and socket compatibility may in fact be a prerequisite. For that reason, it will be included in this document, even though R&D is most likely not required for plug and socket compatibility alone.

The Roadmapping Process

There is no single standard approach for creating a roadmap, but one developed by Sandia National Laboratory is a good fit for the roadmaps being developed by Efficiency for Access.[20] After initial consideration of the scope and boundaries of the roadmap in terms of participants, timeframe, and resources, the steps are:

1. Identify the products to be the focus of the roadmap
2. Identify critical system requirements for those products
3. Specify the major technology areas that can help achieve the critical system requirements
4. Specify the technology drivers and targets in the technology areas
5. Identify technology alternatives and consider their timelines
6. Recommend a subset of the alternatives that should be pursued

This roadmap was prepared based on this process with input from a Technical Working Group (TWG) made up of representatives from SHS companies, PAYG software providers, appliance manufacturers, an industry association, NGOs, and standards organizations.

Given the early stage of market development in the off-grid sector, it is not possible to state numerical targets and timelines for achieving them with specificity as one might do in a more mature market. Nor is it possible at his stage to make definitive recommendations on technology alternatives to be considered. However, this document can serve as a starting point that can help drive progress as the off-grid market continues its rapid growth.

2.0 Scope and Structure of the Roadmap

Products and Critical System Requirements

A roadmap scoping document was created and then revised based on TWG input. The goal of the scoping document was to define the boundaries of the roadmapping effort in terms of products and critical functionality of the systems and appliances being considered. TWG discussions were informed by the DC Local Power Distribution (LPD) approach described by Nordman & Christenson.[21] **Figure 5** is useful for examining the requirements.

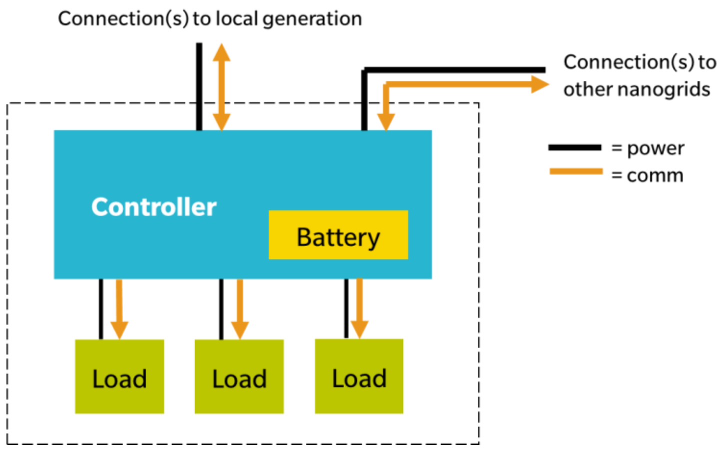


Figure 5: Schematic of local power distribution, termed nanogrid in the figure, but applicable to SHSs. Adapted from (Nordman & Christenson, 2015)

A controller connects to local generation and to loads, as well as to other systems (described as nanogrids in the figure). Applying the figure to a SHS, local generation would be from the solar panel and the controller would contain a battery, as shown, but would also include other hardware such as a charge controller or maximum power point tracker (MPPT). Loads would be lights, phone charging, and any appliances used with the system. An inverter could be internal to the controller to provide integrated AC power, but would more typically be an external load determined by connection to one or more AC appliances.

Currently, SHSs are very seldom connected to each other in a pooled configuration, but there are existing companies that implement this approach.[22, 23] Adjacent buildings in settings such as schools, business, or family compounds can be connected to share power. The application of this figure to minigrids is straightforward as well, except the local generation would be centralized rather than distributed and the systems would usually not include a battery.

The unique feature in the diagram relative to most current off-grid systems is the communication component. With appropriate protocols, loads could be managed by the controller consistent with preprogrammed power management protocols and/or a user interface. The controller could also manage power from adjacent systems or a minigrid. Features not shown in the diagram but appropriate for off-grid systems are a PAYG and/or user interface for system control (via a physical interface or an application). A communication interface for external system monitoring could also be included.

In considering the system described above, the TWG agreed on the products and critical functionalities required, as shown in **Table 1**. "Critical" in this case applies to an ideal system with full functionality achieved. Even if all the critical system requirements were to be achieved and all functions available, systems might be designed with only some of the features included, depending on market objectives.

The focus on system components like controllers, plugs, and cables is obvious based on the system requirements, but the exclusion of AC appliances may not be. Though it is possible that an AC appliance manufacturer could tailor a product for the off-grid market, the assumption is that DC appliances, with their smaller and more focused market, are the most likely to include such features in the near term.

Products	1. DC appliances for use in solar home systems and DC/AC minigrids 2. Power supply controllers for use in solar home systems (PV charge controllers, MPPTs, inverters, batteries) 3. Plugs and cables for use in solar home systems
Critical system requirements	1. DC Appliances that: a. Use standardized plug types consistent with power needs or other requirements b. Can communicate their power needs and status to the power supply module c. Can communicate their operational status and allow for functional control, e.g. with a distributor/repair center/manufacturer d. Can comply with a [standard/standard suite of] PAYG management platform(s) to enable distributor mixing of appliances and consumer use after the payback period 2. Power supply modules that: a. Can communicate with and manage loads b. Can communicate with and manage power with other supplies [adjacent distributed supply, DC/AC minigrids, grid power (mains electricity)] c. Can communicate their operational status and allow for functional control, e.g. with a distributor/repair center/manufacturer d. Can comply with a [standard/standard suite of] PAYG management platform(s), to enable distributor mixing of appliances and consumer use after the payback period 3. Connectors, cables, and plugs that: a. Meet safety and functional requirements for power distribution and appliance loads b. Are standardized and not interchangeable with plugs connected to incompatible supplies or loads

Table 1: Roadmap scope defined in terms of products and critical requirements to be considered.

Technology Areas and Drivers

Having defined the scope of the roadmap from the standpoint of products and functionality, discussions with TWG members informed a decision to divide the desired functionality into the following technology areas: electrical connectivity; power distribution connectivity and communication; general data communication; PAYG data communication; and low cost embedded controllers or other hardware necessary to support these functionalities. This division was informed by a model for managing and optimizing distributed power, Network Power Integration (NPI), also defined by Nordman and Christensen.

This approach would use network layers, a reduced form of the Open Systems Interconnection Model that standardizes the interoperability of communications systems.[24] **Figure 6**shows the NPI layers and functions on the right, with analogous layers for off-grid applications discussed in the TWG on the left. Starting at the bottom, I physical layer corresponds to the electrical connections to deliver the power and the data layer to the communication about the power. The network layer corresponds to the power management of the individual system, with communication between systems being managed at the transport layer. A physical user interface or interface via an application (sometimes referred to as Internet of Things), or PAYG control of the system happen at the application layer.

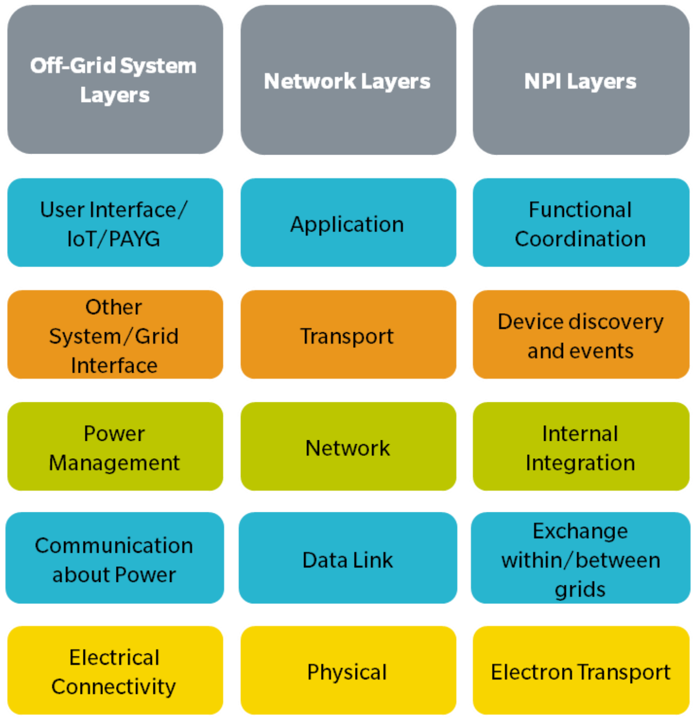


Figure 6: Diagram of network layers in the Networked Power Interface (right) plus mapping to off-grid system layers discussed in Technical Working Group (left) Adapted from. (Nordman & Christenson, 2015)

The off-grid network taxonomy shown in **Figure 6** and the technology drivers required to realize it were developed and discussed by the TWG.

Major Technology Areas		Technology Drivers
Electrical connectivity for plugs, sockets, connectors and cables used in low voltage DC solar home systems		• Industry consensus around electrical requirements, safety, durability, ease of use, cost • No R&D required for plug compatibility alone, though may be linked to choice of connectivity for power management/ general data/PAYG communications
Power distribution connectivity and communication:	External: For controller interface with adjacent distributed supply, DC/AC minigrids, grid power (mains electricity)	• Industry consensus on set of variables to be communicated • Decision about whether to include hardware specifications • Decision about whether power line communication or additional signal lines are used, because plugs, sockets, and cables are affected by this choice • Mostly integration, but some R&D possible
	Internal: For load management in solar home systems	• Decision about whether there are appropriate standards (existing or in development) for DC distributed generation connections or if new ones need to be developed • Decision about whether existing inverter standards are appropriate /sufficient for SHS connection to AC supply • Some R&D possible if existing technology is not appropriate
General data connectivity and communication for external monitoring of appliances and power supply modules		• Industry consensus on set of variables to be communicated • Decision about whether this should be hardware agnostic or use the same hardware as specified for power distribution, keeping in mind the implications for plug type • R&D required
Connectivity and communication for Interoperable PAYG solution for controller and/or appliances		• Decision about feasibility of multi-protocol hardware or some means of translating between PAYG platforms when appliances are integrated into a system • Consensus on whether this can be done without compromising intellectual property or disadvantaging PAYG providers • R&D required
Low cost embedded controllers and other components for implementation of connectivity/control protocols		• Decision about whether industry consensus on protocols and dedicated functionality could aggregate purchasing power and lead to lower cost for embedded controllers in systems and appliances • R&D required

Table 2: Roadmap scope defined in terms of technology areas and drivers to be applied to relevant products to achieve the critical requirements identified in **Table 1**.

3.0 Compatibility and Interoperability Technology Drivers

Electrical Connectivity

Electrical Connectivity for Off-grid Appliances

From the appliance perspective, ensuring suitable electrical connectivity should be (though is not always) synonymous with plug and socket compatibility, which breaks down naturally into appliances that are designed for use in AC systems and those for DC systems. Given the large and established global market share for AC appliances, this report touches only briefly on compatibility for them specifically. However, the situation for AC appliances is of interest when considering how DC appliances might evolve in the off-grid market.

Electrical Connectivity for AC Appliances

Despite more than a hundred years of electricity system development and the establishment of a technical committee (TC23) in 1934, it was not until 1986 that international standards for AC plugs and sockets were agreed (IEC 60906-1 for systems in the 250 V range and IEC 60906-2 for those in the 125 V range). However, only two countries have adopted these standards (Brazil and South Africa); instead, there are currently 14 main plug/socket types, and these do not uniquely correspond to the 8 voltages and 2 frequencies in use around the world.[25] As a result, AC appliances must conform to different national standards corresponding to their target markets.

Appliance manufacturers selling to local markets may wish to simply hardwire the appropriate plug, but those selling globally have adapted to this lack of compatibility by using ports containing standard appliance couplers (under IEC 60320) that connect to power supply cords fitted with a plug that conforms to local markets. This ensures that there is a single design and bill of materials for the appliance, while the quantity and type of power cords can be adjusted to suit market demand.

There are currently 11 pairs of appliance inlets and connectors under IEC 60320, each corresponding to a unique combination of current, temperature, and grounding (earthing) requirements. Voltage is not specified, however, so in some cases the user must still ensure that the voltage rating of the appliance matches that of the electricity supply. A well-known example of this is the C14 inlet found on personal computers, which are shipped with power cords having a C13 connector on one end and a country-specific plug on the other. The top left of **Figure 7** shows a C13/C14 connector/inlet pair, while the top right shows the back of a personal computer with a C14 inlet and a voltage selection switch below it.

(Image copyright Interpower)

(Image copyright Acer)

(copyright Image HP)

(Image copyright Lenovo)

Figure 7: (Upper Left) An IEC 60320 C13/14 appliance connector/inlet pair; (Upper Right) A C14 inlet and voltage switch on the back of a personal computer, used to select between 115 V and 230 V; (Lower Left) A laptop adapter with a C6 inlet; (Lower Right) A laptop adapter with a C8 inlet.

The bottom images in **Figure 7** show laptop adapters that use switched mode power supplies to convert AC voltages to DC. The one on the lower left shows an IEC 60320 C6, 3-pin grounded inlet while the one on the lower right shows an ungrounded C8 inlet. These adapters can accept all standard AC voltage/frequency combinations. Though the AC power cord and plug appropriate to the local market can be provided with the adapter, the two different DC connectors on the other side of the adapter foreshadow the difficulty of a lack of standards for DC appliance connections. In fact, the proliferation of AC adapters with non-standard DC connectors has contributed to the significant electronic waste problem around the world, with old mobile phone chargers accounting for 51,000 tons of electronic waste in the European Union alone.[26]

AC appliances used in the off-grid context may connect to an AC minigrid directly or to a DC minigrid or SHS through an inverter. In these cases, the minigrid or inverter is likely to provide connections that conform to national standards and the user is likely to know the correct voltage where it is necessary. This means that there are not likely to be plug compatibility issues any different from those faced by on-grid users.

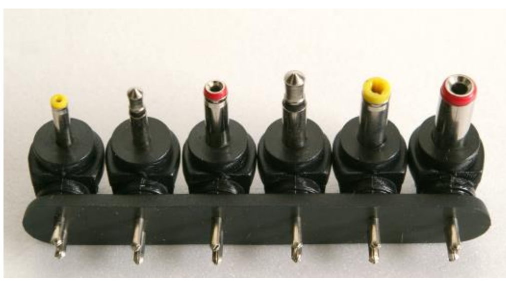
Electrical Connectivity for DC Appliances

Most household devices, such as LED lights, mobile phones, televisions, tablets, and laptops, are native DC devices; that is, they operate internally on DC power. The exception is many motor driven systems, such as refrigerators or air conditioners, which run internally on AC power. However, manufacturers targeting off-grid markets are starting to incorporate brushless DC motors into those products as well, meaning that all electrical products used in off-grid households could run on DC power.

Because power conversion always involves losses, avoiding the use of an inverter or an AC adapter and operating on DC power in SHSs and DC minigrids maximizes efficiency. The fact that DC motors are intrinsically more efficient than AC motors is an additional benefit for motor-driven appliances. Greater efficiency translates into decreased power consumption and operating costs, though overall affordability depends on the relative purchase price of AC and DC appliances.

The debate over whether the efficiency gain is worth the generally higher cost and lower availability of DC appliances today is beyond the scope of this report. However, it is fair to say that cost differences between these appliances are dominated by the current disparity in manufacturing volumes. It is reasonable to assume that if the off-grid market is to scale to meet consumer needs as desired, manufacturing volumes of DC appliances will become far larger and their costs will decline in turn. A positive trend in that direction has been noted by Lighting Global, which reports that market leaders in the off-grid service market are placing increased emphasis on providing greater services through providing access to DC appliances.[27]

The increased prevalence of DC appliances will only serve to exacerbate the lack of compatibility in DC plugs and sockets that exists today. While AC voltage, frequency, and plug configurations are not standardized globally, there are at least national standards to which manufacturers can conform. This is not the case for DC voltages or plug configurations, where differentiation tends to be by manufacturer and not country and there are many more options for DC connectors, including coaxial "barrel-plug" connectors, automotive "cigarette lighter" connectors, as well as USB and Ethernet power connectors. These are in turn covered by many different standards issued by different standards bodies.[28] For example, IEC 60130-10 defines coaxial connectors with five outer diameters and five inner diameters which, in combination, make seven plug types, with no voltage level specified. **Figure 8** shows a few types of DC connectors.



(Photo: Rainer Knäpper, Free Art License, http://artlibre.org/licence/lal/en/)

(Photo: Turbotom1 at English Wikipedia, GNU Free Documentation License)

Figure 8: (Left) Various coaxial "barrel-plug" connectors; (Right) A 12 V "cigarette lighter" plug (Society of Automotive Engineers Standard J563)

Electrical Connectivity for Off-grid Systems

From an off-grid system perspective, the key concerns related to electrical connectivity are voltage, current, and power, which is the product of the two. The lack of standardized mapping of voltages onto DC connectors applies to the ports in a SHS controller just as it does to DC appliances, with the added complication of a range of voltage outputs in a system. In addition, systems must include cables that are appropriately sized for the current required by the devices connected to it, and must manage any voltage drops associated with long cable runs. If a system is plug and play or integrated by a third party, appropriate cables may be provided with it. If, however, appliances are sold separately and are to be added to systems by a consumer, appliance manufacturers may need to provide appropriate cables and consumer education.

Though some component-based SHSs operate at up to 48 V, most plug and play systems operate at 12 V or lower, as do systems covered under the National Solar Mission and Infrastructure Development Company Limited institutional programs in India and Bangladesh referenced in the Market Trends and Segmentation Section. While DC minigrids may distribute power at higher voltages, they typically interface with homes or small businesses using at most 24 V – 48 V DC. The advantage of higher voltage is lower current for the same power needs, which enables the use of thinner, less expensive wires.[ii] As system loads get larger, it will make more sense for them to operate at higher voltages. However, the maximum voltage that can be used is limited by safety concerns, with 60 V DC defined in various IEC standards as the Safety Extra-low Voltage (SELV) limit, though national standards vary.[29]

The details of the costs and benefits of off-grid system voltages are beyond the scope of this roadmap but, ideally, standardization of electrical connections would include a range of design voltages. In practice, the most prevalent need is for charging of mobile phones at 5 V, which means that USB 2.0 Standard A receptacles are nearly ubiquitous in off-grid control boxes. The other most common need is for connections to LED lights, but the output voltages to the LEDs are determined by the system design and the plugs and receptacles are set by the manufacturer. Most off-grid televisions and fans are designed for operation at 12 V. It is not yet clear what voltages will be most prevalent in the design of higher power off-grid appliances.

In surveys of "small electricity systems," Chris Moller of The Open University focused on understanding various aspects of system operations, including electrical connections.[30] Though the number of respondents was small (25) and included some systems with grid connections, the results for DC power support the conclusion that there are numerous types of electrical connections without defined voltages, with the exception of 5 V USB connectors. Companies participating in the Interoperability TWG were also surveyed in an attempt to understand their current practices, but the response rate was quite low, with only a few responses received. However, even these revealed the use of 5 V USB connectors, 12 V barrel connectors, and 12 V cigarette lighter connectors.

The World Bank Group's Lighting Global program has developed quality assurance standards (the Lighting Global Quality Standards) and maintains a quality assurance program for solar products.[31] One can select products on their web site and access a specification sheet, which lists connectors and voltages. However, barrel jack connectors are not identified with specific dimensions. A query regarding whether the test sheets contained this information revealed that they do not, thus there is not even a record of how many types of barrel connecters are in use in Lighting Global Quality Certified Systems. These results point to not only a lack of standardization of DC connections in off-grid systems, but a fundamental lack of knowledge of what types of connections are being used by consumers, apart from those known to suppliers of particular products.

Electrical Compatibility for Off-grid Appliances and Systems

Beyond the issue of electrical connectivity for off-grid systems is that of electrical compatibility. This falls into two categories. One is ensuring voltage compatibility and sufficient current carrying capacity, even if the plug and socket match. This applies to the cables used, as discussed in the previous section, but also to the controller itself. This is to avoid damage to the appliance or the controller as well as harm to the user. This could be addressed through standardized connections or a labelling system that would warn users of incompatibility. Another approach would be to overspecify the system by standardizing at a higher voltage and current capacity, but this would add to costs because of more expensive components.

The other issue is ensuring sufficiency of supply, which is more challenging and places a greater burden on consumers. A user connecting an appliance to the domestic power grid (mains electricity) is unlikely to affect its operation (outside of inadequate capacity on a circuit), whereas excessive load on a low capacity minigrid or SHS may trigger a fault or rapidly exhaust the available energy supply. One approach to the supply sufficiency problem would be to develop labelling schemes to indicate general appliance load/system sizing compatibility. This passive approach would ensure a measure of compatibility, provided the labelling system was understood and employed appropriately, which would require considerable consumer education. A full solution would require active communication between load and supply. Such communication could go beyond sufficiency of supply and include actual power management.

[ii] The current carrying capacity of a wire depends on its resistance per unit length and the square of the current. The resistance per unit length depends on the material and the cross-sectional area of the cable, so lower current enables the use of thinner wires with less conductor, making them less expensive.

Connectivity and Communication for Power Management

Passive Approaches to Electrical Compatibility

An approach recently proposed for IEC consideration by Chris Moller is to have bar code labels placed on connectors supplied with SHSs or appliances, or on the devices themselves, which would contain information on the voltage and current limits associated with their use.[32] A consumer could then scan the connectors or devices with a mobile phone and an application would determine their compatibility. A simplified approach along these lines would be to include LEDs in connectors that would indicate voltage or current incompatibility, but these have the disadvantage of requiring the connection to be made first.

Beyond this basic information about compatibility of the electrical connection, one could also embed information about the overall capacity of the system or power needs of the appliance into a bar code on the system or appliance itself. This would give an indication of whether a given system should be capable of powering an appliance and, if so, for how many hours when its battery is fully charged. Such labelling could also be used to guide consumer selection of appropriate appliances, a feature described in the Off-Grid Refrigeration Technology Roadmap published by the Efficiency for Access Coalition.[33] That roadmap refers to "Selection Software to Support Technical Sales" as one of the technology options to meet market needs for off-grid refrigeration.

Though valuable for equipment selection and compatibility checks, the limitations of passive approaches become apparent when one thinks about systems in actual operation, with seasonal variation in insolation for charging solar PV systems as well as systems that may be powering multiple loads. It would be desirable to have available a more active power management approach, preferably with a degree of user control.

Active Approaches to Electrical Compatibility

Power management of appliances connected to a controller implies that the controller is able to selectively reduce the power consumption of loads connected to its ports. For lighting and some other appliances, this may not actually require communication, insofar as a low state of charge in the battery could be set to automatically dim the LEDs or reduce device power by triggering a voltage or current reduction through specific ports. A technique called droop control could be employed to manage power sharing between loads, or to signal when a device should shift into a lower power mode, but with multiple appliances or in a distributed SHS or minigrid configuration, communication is required.[34]

One immediate consideration for power management communication is what kind of interface could be used between appliances and the control box. A wireless interface could use RF technologies such as Wi-Fi or Bluetooth Low Energy, but these are typically more expensive than a wired connection. Wired connections could take a number of forms, depending on the communication protocol, interface, and associated microcontroller used. This would again introduce the problem of plug and socket compatibility for these connections. One possibility, discussed in Electrical Connectivity above, is for power management functionality to be combined with a user interface (IoT) or PAYG control functionality. In this case, solving the interface problem could create a path for multiple functionalities.

Another concern with power management is enabling the customer to choose which loads to cut back or shed. At any given time, a user may wish to prioritize maintaining temperature control in a refrigerator or ensuring that a television program isn't cut off. This functionality could be implemented via a user interface on the control box, but could also be implemented via IoT functionality on a mobile phone (see the 0).

Connectivity and Communication for Controller Interface

Beyond the use of appliances in off-grid systems, one has to define the boundary of the system and any external interfaces that may be required. For example, it may be desirable for multiple SHSs to be able to share power, or for a SHS or minigrid to be used in an "under grid" context in which consumers use the systems as a supplement to available but unreliable grid power. (The Rocky Mountain Institute estimates that there are 200 million households in the world that are within electricity distribution company territory but receive inconsistent and/or low quality power.[35]) Minigrid developers are concerned about the consequences of the arrival of the domestic power grid and whether their investment will be incorporated into the main grid as distributed generation or instead become a worthless stranded asset. All of these cases require that there be some interface to enable interactions with other systems or the main grid.

DC to DC Connectivity

In many parts of the world, people live in family compounds with multiple buildings. SHSs installed in separate buildings could pool resources via power sharing protocols, as described in Section 2. In addition to implementation by at least the two companies referenced there, this is still an area of academic research.[36, 37] It may be more likely that DC power sharing approaches are implemented first in grid-connected environments on university campuses or between corporate buildings. The EMerge Alliance is an industry association formed to advocate for just this strategy.[38] However, the technologies used in these contexts will probably be too expensive for off-grid applications. Developing an off-grid DC power sharing approach may be an R&D opportunity.

DC to AC Connectivity

Connections between DC systems and AC power are more complicated. In the event that consumers have adopted DC appliances in a SHS, connections to an AC minigrid or the main power distribution grid would require a controller that is able to rectify the AC voltage to supply appropriate DC voltages. In the event that AC appliances are used, these can be connected directly to the grid, though using those appliances when the grid was unavailable would require an inverter. Systems could also be split, with AC appliances connected to the main grid and lighting and phone charging on the SHS side for times during which the main grid is unavailable. Communication may not be required, as switching between the SHS or DC minigrid and the AC grid could be triggered by the absence of AC power or manually by the user.

Most SHS systems would be too small to be taken up as distributed generation by a local utility, but this would ideally be the case for larger systems or minigrids. Inverters to enable that functionality are in widespread use in residential solar PV installations around the world. However, the inverters used for these connections must meet certain standards in order to support power quality and grid reliability. In the United States, for example, “smart inverters” governed by IEEE 1547-2018 are required.[39] In the off-grid context, the amount of power supplied to the grid will be smaller and price sensitivity more acute, so less expensive inverters with reduced functionality may be desirable. This is an area for potential R&D work.

General Data Communication and Internet of Things

Besides power management and connectivity between systems, communication in off-grid systems could be used to support system monitoring, user interface (IoT) and PAYG operation. The first two topics are covered in this section, while PAYG operation is covered in the next section.

Data Communications for System Monitoring

The desirability of remote monitoring of appliance performance is highlighted in both the Efficiency for Access Coalition Refrigeration Roadmap[40] and Solar Water Pump Roadmap.[41] Given the remote locations of many off-grid installations, there is a lack of ready access to repairs and maintenance. Remote monitoring of appliance performance may provide appliance manufacturers, distributors, or repair centers information about poor performance or failures without the consumer needing to report them. Similarly, it is desirable to monitor the health of the battery and the performance of the solar panel in a SHS to see if there are problems at the system level.

Some SHS providers that include PAYG build system performance monitoring into their PAYG functionality. However, a generally applicable, widely accepted protocol for system and appliance monitoring would be beneficial to aid in widespread adoption. A protocol could be designed to report on a comprehensive enough set of parameters for the most sophisticated systems, but actual implementation could rely on passing only a subset of the parameters for systems that needed less. It would be necessary to define the parameters to be monitored, the protocol to be used, and the interface for the communication. If the protocol were made open source, it could be subject to continuous improvement, while the competitive advantage of companies using the protocol would be derived from the quality of their data handling and user interface.

In areas with access to a mobile network, each data collection location could be connected to the network. Alternatively, multiple data collection points could connect to a central location that then connects to the network. In areas without access to a mobile phone network, sensor data may be collected and stored, transmitted locally to a user’s mobile phone, and then uploaded when the user enters network service range.

Data Communication for User Interface (Internet of Things)

As described under power management (Section 0), user control of appliances via an interface would be desirable to enable control over prioritization of services. Generalizing user control to an application accessible by mobile phone would bring this capability into a category of functionality often identified as the Internet of Things (IoT). The International Telecommunication Union defined IoT in 2012 as “a global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies.”[42] However, years on, 92% of mobile industry respondents identified fragmentation as a “major or moderate” issue, with connectivity technologies and management identified as the areas in greatest need of standardization.[43]

Given the lack of consensus on IoT technologies in mature markets, it is probably most appropriate for the off-grid sector to develop low-cost, dedicated solutions that can be broadly replicated. Such solutions could be built around system monitoring or PAYG communication technologies and interfaces to reduce costs and complexity.

Interoperable PAYG Protocol

As described in Section 0, a SHS with PAYG is typically a packaged, plug and play system with lighting and sometimes appliances included. The appliances are owned by the company that manufactures and distributes the systems, sometimes with the intent of transferring ownership to the consumer via the PAYG contract (the asset ownership model) or sometimes with ownership retained by the company (the energy as a service model). In either case, the security of the appliance is critical to the transaction. In the future, bulk purchase commitments and consumer financing of appliance purchases may be supported by governments and/or international financial institutions, which would take the appliances off the books of the companies. However, those institutions would probably still wish to track their assets, which could be done through the same or a separate PAYG solution.

Ensuring that an appliance included in a PAYG system is secured involves customizing the appliance for use with that system’s PAYG platform, which can be unique to the company or one of several available third-party implementations. The appliance is locked out to prevent functioning unless it receives a correct code via machine-to-machine (M2M) communication. This may involve the user entering a code via keypad on the SHS controller or on their phone, or receipt of a signal directly by the controller via a mobile network. In any case, the appliance itself must have an M2M solution and a microcontroller if it is to be secured to work only when authorized.

Though these approaches all achieve their core purpose of securing the appliance, it is less than ideal for an appliance manufacturer to have to implement multiple PAYG solutions for a single product and no doubt adds to product costs in a very cost-sensitive market. As a result, an interoperable solution that would allow multiple PAYG platforms to work with a single appliance would be highly desirable.

To date, PAYG operations have been focused on repayment for bundled systems, so the focus on the appliance has been limited to its securitization as part of the bundle, rather than accounting separately for appliance operation and payback. This could conceivably change in the event that more expensive appliances are sold under their own, separate PAYG contracts. Similarly, as described in Section 0, IoT applications could be written for control of specific appliances. Joint PAYG and IoT solutions that could be used at both the appliance and system levels would greatly simplify implementation costs for appliance manufacturers.

One important consideration is that there are third party PAYG providers whose business model may be affected by these changes. It would be desirable for such companies to participate in the process of developing an interoperable protocol to ensure that assets are secured sufficiently for their needs and that they are able to maintain the key backend features of their business that are most important to them: payment mechanisms and data related to their customer base. The goal would be to standardize the front-end interface and protocol to improve market efficiency while allowing companies to differentiate themselves based on their backend financial and customer relationship management solutions.

The Efficiency for Access Research and Development Fund was launched in November 2018. One of the winners of the first round of funding awards was Solaris Offgrid, which is undertaking a project called “open source standardized Pay-As-You-Go communication protocol.”[44] Because discussions of this topic were already underway in the TWG at the time of this grant, Solaris is channeling their outreach and reviewing their progress through the TWG. The first review and discussion of their proposal took place in May 2019, with work currently proceeding.

Low Cost Embedded Controllers and Other Components

A longer-term objective arising from interoperability in the off-grid sector is increased purchasing power and ultimately lower costs for system components. Interoperable system monitoring, IoT, and PAYG solutions could enable wider scale purchasing of key interface components, including microcontrollers designed to enable those solutions. The history of technology development and deployment is that standardized solutions lead to larger volumes which lead to decreased costs. Because achieving cost reductions depends on the development of widely adopted solutions, a focus on this topic necessarily comes after agreement on those solutions.

4.0 Summary of Industry Actions and R&D Priorities

Summary of Industry Actions

As described in Section 0, ensuring the compatibility of existing off-grid technologies through industry-wide agreement is typically something accomplished through creation of standards rather than a roadmap, though the process can be less formal than standard-setting. The example from other industries is that of a company or group of companies deciding to work together to agree on a common approach. This informs the recommendation that the off-grid industry should identify companies willing to lead and/or participate in working groups focused on:

- Defining uniform requirements for electrical connectivity
- Deciding on approaches to connectivity in support of load management in SHSs, which might be accomplished though industry consensus but might also lead to specifying R&D activities to improve the available options
- Informing and supporting the R&D activities specified below

Exactly how an industry group is formed or led should be a focus of dialogue between individual companies or industry associations and policymakers, aid organizations, development finance institutions, philanthropies and others focused on achieving SDG 7.1. Hopefully this roadmap can inform those discussions.

Summary of R&D Priorities

The more typical output of a roadmap is a set of priorities for R&D activities that support development of the technologies needed to meet future business requirements. Based on the technology drivers identified in this roadmap, the recommendation for R&D activities is:

- Development of power distribution connectivity interfaces and protocols to support load management in solar home systems, depending on industry consensus around whether such R&D is necessary
- Development of power distribution connectivity interfaces and protocols to support the ability of SHS controllers to interface with other SHS systems, DC minigrids, or AC minigrids
- Development of general data connectivity and communications interfaces and protocols for remote monitoring of systems and appliances
- Development of interfaces and protocols for an interoperable PAYG solution for controllers and appliances

The final technology area identified in the roadmap, low cost embedded controllers and other components for implementation of the communication protocols listed above, should be pursued after sufficient progress is made to support an industry consensus on the bulk purchasing requirements necessary to enable lower cost.

The R&D recommendations above are not specified in priority order, as research is underway to some degree in all these areas and it makes sense to be opportunistic in project support. However, should limitations in available funding drive the need for prioritization, the industry convening process used in support of the areas identified in the previous section could be used to gather input on funding allocation.

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