Title
Connections beyond the margins of the power grid: Information technology and the evolution of off-grid solar electricity in the developing world

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Connections beyond the margins of the power grid
Information technology and the evolution of off-grid solar electricity in the developing world

By
Peter Michael Alstone

A dissertation submitted in partial satisfaction of requirements for the degree of Doctor of Philosophy in Energy and Resources in the Graduate Division of the University of California, Berkeley

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Fall 2015
Abstract
Connections beyond the margins of the grid

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Doctor of Philosophy in Energy and Resources

University of California, Berkeley

Professor Daniel M. Kammen, Chair

This work explores the intersections of information technology and off-grid electricity deployment in the developing world with focus on a key instance: the emergence of pay-as-you-go (PAYG) solar household-scale energy systems. It is grounded in detailed field study by my research team in Kenya between 2013-2014 that included primary data collection across the solar supply chain from global businesses through national and local distribution and to the end-users. We supplement the information with business process and national survey data to develop a detailed view of the markets, technology systems, and individuals who interact within those frameworks. The findings are presented in this dissertation as a series of four chapters with introductory, bridging, and synthesis material between them.

The first chapter, *Decentralized Energy Systems for Clean Electricity Access*, presents a global view of the emerging off-grid power sector. Long-run trends in technology create “a unique moment in history” for closing the gap between global population and access to electricity, which has stubbornly held at 1-2 billion people without power since the initiation of the electric utility business model in the late 1800’s. We show the potential for widespread near-term adoption of off-grid solar, which could lead to ten times less inequality in access and also ten times lower household-level climate impacts. Decentralized power systems that replace fuel-based incumbent lighting can advance the causes of climate stabilization, economic and social freedom and human health.

Chapters two and three are focused on market and institutional dynamics present circa 2014 in for off-grid solar with a focus on the Kenya market. Chapter 2, “*Off-grid Power and Connectivity*”, presents our findings related to the widespread influence of information technology across the supply chain for solar and in PAYG approaches. Using digital financing and embedded payment verification technology, PAYG businesses can help overcome key barriers to adoption of off-grid energy systems. The framework provides financing (or energy service payment structures) for users of off-grid solar, and we show is also instrumental for building trust in off-grid solar technology, facilitating supply chain coordination, and creating
mechanisms and incentives for after-sales service. Similar models are also being tested and launched for on-grid electricity (pre-pay energy meters) and agricultural water pumping among others. While there is a clear potential to extend the reach of critical infrastructure networks, there are also important concerns for achieving equitable and sustained access. Some are at the business network level, where telecommunications firms have a unique role as gatekeepers and enablers of mobile communication systems and (sometimes) also competing participants in the emerging PAYG market. Another is the importance of balancing privacy and the value of data-driven technology systems like PAYG. We talked with users who both recognized the value in their personal data and were concerned about widespread sharing beyond the boundary of the retail-facing firms that they interact with. Overall the work highlights how information and energy systems are co-evolving at the edge of the grid. Chapter 3, _Quality Communication_, delves into detail on the information channels (both incumbent and ICT-based) that link retailers with regional and global markets for solar goods. In it we uncover the linked structure of physical distribution networks and the pathway for information about product characteristics (including, critically, the quality of products). The work shows that a few key decisions about product purchasing at the wholesale level, in places like Nairobi (the capital city for Kenya) create the bulk of the choice set for retail buyers, and show how targeting those wholesale purchasers is critically important for ensuring good-quality products are available.

Chapter 4, the last in this dissertation, is titled _Off-grid solar energy services enabled and evaluated through information technology_ and presents an analytic framework for using remote monitoring data from PAYG systems to assess the joint technological and behavioral drivers for energy access through solar home systems. Using large-scale (n ~ 1,000) data from a large PAYG business in Kenya (M-KOPA), we show that people tend to co-optimize between the quantity and reliability of service, using 55% of the energy technically possible but with only 5% system down time. Half of the users move their solar panel frequently (in response to concerns about theft, for the most part) and these users experienced 20% lower energy service quantities. The findings illustrate the implications of key trends for off-grid power: evolving system component technology architectures, opportunities for improved support to markets, and the use of background data from business and technology systems.

Overall the work reveals both opportunities and pitfalls in a combined information-energy system. With increased visibility and control of the system there are opportunities to better support the market, but there are often disincentives to share certain data for private sector actors that operate the decentralized power system and frictions at the interface of mismatched information systems. If barriers to interoperability and scale are addressed, basic human needs for energy can be met by solar at an accelerated pace through connections to emerging information technology and business networks that extend beyond the margins of the grid.
dedicated to Andrea, Salvador, and Billie
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Core funding for this work came from the Environmental Protection Agency (EPA STAR Fellowship FP917428) and the National Science Foundation (BCC-SBE Award 1338539). Prior and to concurrent to my work on this dissertation I was a core contributor to the Lighting Global program’s Quality Assurance, Market Research, and Policy Outreach efforts. Concurrent to the dissertation, I partnered with Lighting Global to create a research partnership for Kenya field research (mentioned above). Building on the scope of work achievable with funding through the NSF and EPA, Lighting Global supported a full-time field research and analytics student assistant who participated through the course of the project (N.T.B. at Humboldt State University) and coverage for portions of the local field staff time. Lighting Global also co-released a series of Market Research Reports that our research team developed.
CHAPTER DETAILS
This dissertation combines a portfolio of work (each of the four main chapters) that was published separately in the academic and institutional press. In this informational section I include the full bibliographic details, abstracts, and a description of my and other authors’ contributions.

Chapter 1

Decentralized energy systems for clean electricity access


Abstract: Innovative approaches are needed to address the needs of the 1.3 billion people lacking electricity, while simultaneously transitioning to a decarbonized energy system. With particular focus on the energy needs of the underserved, we present an analytic and conceptual framework that clarifies the heterogeneous continuum of centralized on-grid electricity, autonomous mini- or community grids, and distributed, individual energy services. A historical analysis shows that the present day is a unique moment in the history of electrification where decentralized energy networks are rapidly spreading, based on super-efficient end-use appliances and low-cost photovoltaics. We document how this evolution is supported by critical and widely available information technologies, particularly mobile phones and virtual financial services. These disruptive technology systems can rapidly increase access to basic electricity services and directly inform the emerging Sustainable Development Goals for quality of life, while simultaneously driving action towards low-carbon, Earth-sustaining, inclusive energy systems.

Author Contributions: P.A., D.G. and D.M.K. conceived the work. P.A. designed and implemented the analysis and was lead author. D.G. and D.M.K. contributed to the analysis and writing.

Chapter 2

Off-grid power systems and connectivity


Abstract: Pay-as-you-go (PAYG) solar home systems are a fast-growing segment of the off-grid power sector. Our research team studied the PAYG market in Kenya, where there are (circa early 2015) twice as many active deployments of PAYG as any other country in the early market. Working with M-KOPA and SunnyMoney in depth we obtained customer surveys for users of
PAYG (n=205), combined with long-term retail market study, focus groups, and structured interviews. In a global survey of firms we document diverse approaches with variations in technology platform for payment and verification, pricing strategy, offer type, system scale, and business partnership strategies. We found strong evidence PAYG accelerates energy access, with early indications of scale on the order of a factor of two higher adoption rates among people who are offered an opportunity to buy. This acceleration derives from a combination of financing to reduce liquidity barriers for initial purchase and increased trust in the quality of the technology system and likelihood of support from the original seller. Along with supporting rapid deployment of solar home systems, the remote connectivity and business process data that are available (in varying degrees) from PAYG systems hold promise to support new approaches to market research and after-sales service. We also identify a set of critical issues for understanding and supporting the market. One is the role of telecommunications firms that operate important mobile money systems and may also compete in the PAYG market with their own or a partner’s offering. We also identify urban-to-rural subsidy that is implicit in uniform national pricing, a disconnect between financial payback and the human development outcomes from systems that are disabled after partial payment, and important privacy concerns raised by users with respect to repayment and system operations data use.

Author Contributions: P.A. was lead author and analyst, and overall lead on the research project, D.G. co-authored and contributed to analysis. P.A., D.G., and N.T.B. conducted the field research. A.J. and D.K. are advisors and contributed to framing and final authoring.

Chapter 3

Quality Communication


Abstract: The flow of information and goods defines supply chains for solar, like any electronic good. In this study we uncover the structure of flows for goods and information in the Kenya market with a focus on information about product quality and performance, a key set of factors for the economic, social, and environmental performance of off-grid solar. The basis for our research is a set of retail-level surveys in three market centers in Kenya (n=150) conducted in May and June 2014 (following up on surveys in 2009 and 2012 in the same locations), which is combined with solar customer surveys and structured interviews across the global industry, from capital cities to rural villages. We show how solar products with quality verified by Lighting Global flow through a range of supply chains that are parallel to and often separate from incumbent electronics goods supply chains. The structure of the business networks indicate (and our research supports) the high value of reaching distribution-level buyers with information about product quality, since their purchasing decisions drive retail choice sets. At the retail level we identify new opportunities for reaching retail sellers through information technology (e.g.,
social media, mobile internet), but traditional channels (paper flyers, word-of-mouth, etc.) continue to be highly valued as well. Beyond active communication, there are also subtle and direct cues about quality available and utilized by buyers and sellers in the supply chain. These include branding around firms or technology, experiential accounts, and availability and placement of products in market settings.

**Author Contributions:** N.T.B was lead author of the report and processed the data. P.A. co-authored the report, designed the field research, and was overall lead for the research effort. P.A., D.G., and N.T.B. conducted the field research. P.A. and A.J. designed and conducted past field research efforts leading to this report. A.J. and D.K. are advisors and contributed to framing and final authoring.

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Chapter 4

**Off-grid solar energy services enabled and evaluated through information technology**


**Abstract:** Advances in the reach and affordability of information and communication technology (ICT) enable new architectures and frameworks for providing decentralized energy services. ICT enables remote payment, monitoring, evaluation, and support of off-grid solar electricity systems that provide vital human-needs service to people without the advantage of a reliable electricity connection. Our work focuses on the particular instance of a pay-as-you-go off-grid solar system (PAYG) in Kenya: the d.light D20-g product, distributed through M-KOPA between November 2013 and November 2014. We use mixed-methods, combining 1,112 hourly monitoring datasets with satellite-derived solar resource monitoring in an analytic framework informed by 4 focus groups, detailed surveys on utilization for a subset of 135 users, and extensive experience in the Kenya market. PAYG users in aggregate behave in a way consistent with co-optimization of electricity service quantity and reliability constrained by the available solar electricity resource and architecture of the system. The average user consumes 70% of the electricity that is technically possible given the maximum solar generation potential, but experiences 90% better reliability, with fewer than 5% of hours without at least some available electricity. We find energy demand is elastic given the available solar resource and external social factors also play a role. Half of users frequently move their solar panels (i.e., bringing them indoors, often to protect against theft) reducing the effective solar resource by 30%, and eventually leading to 18% less electricity provided and consumed (~2 Wh/day, enough to power a standard mobile phone). For 3 billion people globally without access to the grid or with unreliable grid connections, balancing quantity, certainty, and the cost of energy service in the context of natural, built, and social systems is critical for improving energy access. The ICT systems that support this analysis could (if key privacy and data access barriers are overcome) provide channels for large-scale monitoring and assessment that accelerates clean energy access globally.
Author Contributions: P.A. conceived of the work, directed the field research, made industrial research partnerships, conceived and conducted the analysis, and drafted the article. A.J. and D.K. are past and current research advisors and collaborators, provided comments on the study framing and methods, and contributed to authoring the final draft.
People living on the ‘margins’ in the developing world are often beyond the reach of key infrastructure and social networks that are vital for meeting basic human needs, improving livelihoods, and providing opportunity. One in seven people on Earth currently do not have access to modern electricity (and one in five has unreliable access). Relying on inefficient alternatives like fuel based lighting and dry cell batteries both amplifies the structural inequality that underlies a lack of access and results in harms to the climate (1–3), public health (4–6) economic opportunity, and social freedom (7,8). How much more productive, inclusive, and equitable could the global community be if the situation were addressed? With newly available technology options for energy and information systems, there are new opportunities to take a combined information-energy systems approach to addressing access gaps (9,10). This dissertation develops tools to explore the potential and reality of using information technology systems to understand and accelerate electricity access through decentralized solar power.

The past decade has seen rapid shifts in access to ICT in both the developing and developed world. The notion of globally ubiquitous mobile phones has rapidly progressed from a faint prospect at the turn of the 21st century to reality; today there are 90 mobile phone subscriptions per 100 people in developing countries—about 20 times more than in 2000. In the developed word there are 25% more mobile phone accounts than there are people (11). Smartphones, which put powerful computers (often with broadband connectivity) in peoples’ pocket, are the next wave. There are one billion in service today and the International Telecommunications Union expects four billion by 2017, with widespread access that includes the developing world (12). A key enabler of rapid scale-up in mobile communications is the energy efficiency of computing, which has increased following a power-law, leading to new possibilities for storing, managing, and processing data (13). Mobile devices along with Internet broadband, personal computing, and other ICT have quickly grown into a global technology system with widespread and access and increasing capabilities.

The pace of clean energy development has unfortunately lagged information technology. Some of the same nations that experienced growth from 0-90%+ access to mobile phones over the last decade have had stagnant electricity access rates in the low 10’s of percent. Leveraging ICT-based information flows as a catalyst for energy system development is promising but in its infancy, particularly in off-grid and rural settings (14). In the coming decades, 10+ billion new ICT-enabled appliances and systems could be put into service on and off the grid as information-energy systems converge(15).

In ongoing policy and popular discussions around off-grid electricity, even the term “off-grid” is challenged as it has become clear that the binary on- or off-grid classification is insufficient for understanding an evolving energy technology system. Some use the moniker “beyond the grid” to describe stand alone (mostly solar) energy systems, associating off-grid solar with progress; it is often used by boosters of the emerging off-grid power industry (16). There is also an improved understanding of the dynamics for grid connections, where reliability concerns and the marginal
costs (and pricing) of connection can present a barrier to access for both remote households and businesses and also for those in sight of power lines, or, “under the grid (17).”

In response to an evolving understanding of the dynamics of energy access, the policy framework for measuring progress is evolving from a binary (i.e., on/off grid) or linear (i.e., energy ladder) model of access towards a structure with multidimensional energy technology stacking (18). For example, a person using solar for basic household lighting and paying fees for recharging mobile phones at a nearby shop would not simply be off-grid, or for that matter fully served by a solar home system. We recognize there are degrees of access to service with differences in quantity, reliability, cost, and other key features. These new models for measuring energy access can directly inform meeting sustainable development goals (19).

The title of my dissertation, Connections beyond the margins of the grid, highlights the potential for progress on energy access through connectivity-driven technology systems and in the context of both old and new challenges to overcome for reaching those on the margins of society. We document in Chapter 1 how access through connections to either centralized or decentralized energy infrastructure systems requires support from other networks as well. For obtaining a connection to the typical electric grid people do not just need physical proximity to infrastructure, but also a degree of political power and economic inclusion (2). People without electricity are not strictly disconnected from social and technology networks. Many may have access through some but not all of the networks of support that are vital for initiating and sustaining electricity access. For them, the rapid emergence of access to mobile phones (20) has opened up new options for connection between decentralized users and centralized networks of power (21). These networks can provide links with financing for off-grid solar, link rural businesses with distribution networks for high-quality electronics from centralized production, and provide valued bi- and multi-lateral information channels that support markets from household to global scale.

There are key challenges, however, for achieving widespread adoption of even small-scale electricity technology systems. Progress could be slow without financing and other support that bridges global markets for capital and electronic goods with the great diversity of local contexts where people ultimately purchase and use off-grid solar. Chapters 2 and 3 are part of a series of reports that were originally released by Lighting Global, a World Bank Group program with a mission to “catalyze markets for off-grid energy.” The chapters are based on work by a research team I lead in 2013-2015 with a focus on the Kenya market, building on field research extending back to 2008.

\[\text{Prior and to concurrent to my work on this dissertation I was a core contributor to the Lighting Global program’s Quality Assurance, Market Research, and Policy Outreach efforts. More detail on my relationship with the program is in the acknowledgements section in the front matter.} \]
Chapter 2, “Off-grid Power and Connectivity”, presents our findings related to the widespread influence of information technology across the supply chain for solar with a particular focus on pay-as-you-go (PAYG) business models. Using digital financing and embedded payment verification technology\textsuperscript{b}, PAYG businesses can help overcome key barriers to adoption of off-grid energy systems. The framework provides financing (or energy service payment structures) for users of off-grid solar, and we show is also instrumental for building trust in off-grid solar technology since the risk of early failure or poor performance is shared between the buyer and seller. Improved levels of connectivity in PAYG business networks can also facilitate supply chain coordination and creating visible mechanisms and incentives for after-sales service. There are also critical issues and potential barriers. Some are at the business network level, where telecommunications firms have a unique role as gatekeepers and enablers of mobile communication systems and (sometimes) also competing participants in the emerging PAYG market. Another is the importance of balancing privacy and the value of data-driven technology systems like PAYG. We talked with users who both recognized the value in their personal data and were concerned about widespread sharing beyond the boundary of the retail-facing firms that they interact with. Overall the work highlights how information and energy systems are co-evolving at the edge of the grid.

Chapter 3, Quality Communication, delves into detail on the information channels (both incumbent and ICT-based) that link retailers with regional and global markets for solar goods. In it we uncover the linked structure of physical distribution networks and the pathway for information about product characteristics (including, critically, the quality of products). The work shows that a few key decisions about product purchasing at the wholesale level, in places like Nairobi (the capital city for Kenya) create the bulk of the choice set for retail buyers, and show how targeting those wholesale purchasers is critically important for ensuring good-quality products are available.

Chapter 4, the last in this dissertation, is titled Off-grid solar energy services enabled and evaluated through information technology and presents an analytic framework for using remote monitoring data from PAYG systems to assess the joint technological and behavioral drivers for energy access through solar home systems. Using large-scale (n \textasciitilde 1,000) data shared with us from a large and growing commercial PAYG business in Kenya (M-KOPA), we show that people tend to co-optimize between the quantity and reliability of service, using 70\% of the energy technically possible but with only 5\% system down time. Half of the users move their solar panel frequently (in response to concerns about theft, for the most part) and these users experienced 20\% lower energy service quantities. The findings illustrate the implications of key trends for off-grid power: evolving system component technology architectures, opportunities for improved support to markets, and the use of background data from business and technology

\textsuperscript{b} Digital financing means using “mobile money” or other forms of mobile phone enabled payment to repay a loan or an ongoing service fee that is inherently financed. Embedded payment verification is a system that uses either onboard radio connectivity or a keypad input to unlock service from devices in the household when the payments are processed.
systems. Meter data from both on- and off-grid power systems could be a valuable tool for improving the environmental and economic performance of energy technology systems if key privacy issues are resolved to protect users from harm due to data breaches and unwanted applications.

Combined information-energy technology systems are already demonstrating that they can effectively not only reach beyond the margins of the grid, but also that they can redefine what it means to be served by modern energy services. The networks of support (ICT and retail goods distribution) have broader and more flexible reach than centralized electricity distribution infrastructure. With financing and shared risk of technology failure the price and trust barriers to entry for the poor who are on the margins of society can be lowered. Scalable and modular decentralized energy systems have a levelized cost of energy that is higher than the average cost on the grid (2), but on the margin where grid connections are costly and often unreliable they offer an increasingly viable alternative to incumbent fuel-based lighting and other low-value service options.
Chapter 1

Decentralized energy systems for clean electricity access

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Abstract

Innovative new approaches are needed to simultaneously address the needs of the 1.3 billion people lacking electricity while also transitioning to a decarbonized energy system. With particular focus on the energy needs of the underserved, we present an analytic and conceptual framework that clarifies the heterogeneous continuum of centralized on-grid electricity, autonomous mini- or community grids, and distributed, individual energy services. A historical analysis shows that the present day is a unique moment in the history of electrification where decentralized energy networks are rapidly spreading based on super-efficient end-use appliances and low-cost photovoltaics. We document how this evolution is supported by critical and widely available information technologies, particularly mobile phones and virtual financial services. These disruptive technology systems can rapidly increase access to basic electricity services and directly inform the emerging Sustainable Development Goals for quality of life, while simultaneously driving action towards low-carbon, Earth-sustaining, inclusive energy systems.

Contributions: P.A., D.G., and D.K. conceived of the work. P.A. designed and implemented the analysis and was lead author. D.G. and D.K. contributed to the analysis and writing.

Acknowledgements: P.A. was supported by the EPA STAR graduate fellowship, D.G. by the NSF Graduate Research Fellowship Program, and all were supported by NSF grant SMA-1338539, Information-Energy Nexus Research Network. We acknowledge the valuable contributions of data from the Lighting Africa program (where P.A. is also a contributor), the Kenya Bureau of Statistics, and multiple institutions and organizations that publicly share the critical data on energy systems that we assembled in this work. We are grateful for helpful
discussions on super-efficient appliances with Arne Jacobson, Amol Phadke, and others at Humboldt State and LBNL. Thanks to Nick Bryant for collaborating on fieldwork that informs our discussion of ICT and energy. This work benefited greatly from feedback provided by participants in seminars at U.C. Berkeley and from three anonymous reviewers, who provided insightful comments on both the details of the analysis and larger theoretical framework.
Global Energy Challenges
Two critically important and interlinked challenges face the global community in the 21st century: the persistence of widespread energy poverty and intensifying human-driven climate disruption (1, 2). These crises are inexorably linked through the technology systems that underlie them. Although electricity networks have connected billions of people with relatively low cost and high value energy, the resultant emissions have become the primary driver of climate change (1). Furthermore, despite significant growth in the extent of centrally planned electricity networks, billions worldwide still lack even the most basic or reliable services (2). Meeting the needs of the developing world with modern energy and other infrastructure technologies is a critical task for improving quality of life and enhancing human development (3, 4).

However the notion of universal electrification is a key point of contention for negotiations on climate change mitigation (5, 6). The supposed conflict between energy services and mitigating emissions exists partly because of the prevailing paradigm for electrification in the industrialized world, i.e. through centrally planned and carbon-intensive power systems with high levels of demand and low end-use efficiency. (7) Widespread adoption of the same systems at the same demand levels as rich nations poses a clear barrier to climate stabilization (8). Despite the undisputed social value of access, without significant changes to the paradigm of electrification, a billion people are expected to remain isolated in 2030 (9). Eighty percent of those projected to remain in deprivation live in rural areas, where the lack of modern infrastructure and services also directly result in low resilience to the harmful effects of climate change, such as declines in agricultural productivity, increased spread of mosquito-borne diseases, and increasing losses of life and property due to extreme weather events (1, 2, 10).

To clarify the potential of technological, political, and market mechanisms to sustainably address global energy needs, we present a framework to evaluate the opportunities to manage energy and information resources over vastly different scales of service delivery. Focusing on electricity access for the poor and unempowered, we (1) explore the links between access to electricity and human development; (2) consider the historical trajectory of global electrification and (3) describe the implications of an emerging continuum of technology systems that provide access to electricity by harnessing now-ubiquitous information technology systems to create new models for decentralized power. We conclude with a first-order model of technology transitions that emphasizes an alternative technology pathway to the status quo, built on household expenditure data, observational evidence, and the relationships we observe between household spending, service level, and emissions. Using Kenya as an example, we estimate service equity and emissions intensity effects for switching from fuel-based lighting to off- and on-grid power.

Electricity and Human Development
Thus far, progress towards eradicating energy poverty has been insufficient in scale and pace. Un-served and under-served populations still primarily rely on low-efficiency open flames for lighting (11) that is often inadequate (11), incurring substantial economic costs (12) and increased
health(13) and safety risks(14). Greenhouse gas (GHG) emissions from fuel-based lighting are significant(11), particularly black carbon from open-flame wick lamps(15). The off-grid poor also devote significant time and money to recharge mobile phones (16, 17), which are used by 72% of people in low-to-middle income countries, a twenty-fold increase since 2000(18). Mobile phones are a critical basic needs technology that provides valuable services that link people with family, allow for participation in the market place through mobile banking and mobile money transfers, and facilitate a greater level of access to information overall(19). Both lighting and telecommunications are foundational to basic needs and highly valued, as is revealed by the high prices people are willing to pay—in time, money, and risk—in the absence of better alternatives.

Access to electricity is closely linked with improvements in human development including productivity, health and safety, gender equality, and education (2, 13, 14, 16, 17). Much of the research broadly describing quality of life and electrification stems from the pioneering insights of Goldemberg, Johansson, Reddy and Williams (20), who demonstrated a clear correlation between human development and electricity consumption per capita (kWh/capita, which suggested a relationship with steep gains for the first 2,000-4,000 kWh/capita-year and greatly diminishing marginal returns to human development for consumption beyond that basic-needs level) (21). The kWh/capita metric thus became a de facto indicator for progress on energy access, and has been explored in depth, especially by those attempting to determine the direction of causality between consumption and development (21-25).

Inspired by these seminal early studies, Figures 1 and 2 show a new set of relationships based on the fraction of people with electricity access (as defined in national censuses and household surveys—typically a non-specific, legal connection to the grid). Unlike consumption-based relationships that exhibit an inverse power law decline in returns to human development, we show that access is first-order linear predictor of HDI along with an important set of selected Millennium Development Goals (MDG) over its full range (see Supplementary Material for more details and additional plots). This is consistent with an aggregate view of household-level diminishing returns on energy consumption, where the initial applications of energy that are prioritized are also the most valuable for improving peoples’ lives, followed by less valuable applications.

While electricity access is highly correlated with several development indicators, it is not the only factor at play and broad-scale metrics fail to tell the complete story. The underlying relationship between development and access cannot be extricated simply from macro data. There are important technological, social and institutional dynamics that determine the value of access, including intra-household power dynamics, electric grid management, geographic diversity, political relationships, and concurrent access to complementary technology (22, 23). The context of access matters as well. Meeting time-sensitive demands at critical facilities like hospitals, schools, and agricultural processing mills, and is vital. Although it is difficult to determine causality (24, 26, 27), there is a strong case that electricity access is a necessary, but not sufficient, condition for improving human development (17).
A direct measure of electricity access is currently missing from official development tracking but has been proposed for the Sustainable Development Goals, an update to the existing MDG (17), and in the UN *Global Tracking Framework* for energy access (2). Because electricity access is more complex than “on or off the grid”, a new approach is in discussion to effectively track progress of this metric (2, 28). The source power capabilities, reliability, and access to appliances all strongly determine the value of access and are often discussed in terms of a household energy ladder (2, 29), with high-value yet low-power services acquired first (mobile phone charging, lighting) followed by a prototypical stack including fans, television, refrigeration, heating, motive power, and others that all provide service contributing to quality of life (2).

![Figure 1: The relationship between access to electricity and human development index (HDI) for 2000-2010. All the data points are on a country level for a particular time. The individual, country-level regression slopes over time are indicated on the figure, along with a full sample regression. The distribution in slope on a country level shown in the inset box plot indicates the global relationship holds within countries over time (typically). In that inset, the box demarcates the 25th, 50th, and 75th percentile in slope with whiskers out to 1.5x the inter-quartile range and outliers displayed as points, with three outliers significantly outside the scale. These significant outliers are countries with high levels of access, ~99%, so small changes in HDI have large effects on the slope.](image-url)
Figure 2: The relationship between access to electricity and selected Millennium Development indices (a-d) for 2000-2010. All the data points are on a country level for a particular time. The coefficient of determination ($R^2$) values for the full-sample linear regression are displayed on the figure panels. Additional development indices are found in Supplemental Figure S1.

Power Network Growth and Constraints
The expansion of electricity access is fundamentally a process of networks forming and extending in the context of technological innovation with support from complementary systems of capital, institutions, and information. Innovation along any of those dimensions can lead to growth, but only to the extent of support from the remaining complementary networks (as Hughes described in his seminal historical synthesis of early power grids, *Networks of Power*). In the case of electric utilities, the genesis occurred in 1882 with the Pearl Street Station in New York City. Over the coming decades, these firms were further enabled by technology innovation across supply and demand technologies (including dynamo generators, AC transmission and distribution, and relatively efficient lighting and motors that occurred in the late 1800’s and early 1900’s), and catalyzed by the development and spread of a new utility business model for selling electricity on a commercial basis. Thus, utilities created a disruptive technology system that leveraged networks of multinational enterprise, transportation (particularly sea freight and railroads) and capital to grow and (mostly) displace an incumbent global structure of fuel-based lighting and non-electric mechanical power (30).
Following this early private sector activity, the expansion of grids to reach the poor and unserved rural communities also became a priority for policy makers, as it became clear that private actors lacked the incentives to do so. Initiatives like the Tennessee Valley Authority of the 1930’s continue to be echoed today by work throughout the developing world, where the issue of access remains. Our analysis of the archival record in Figure 3 shows that since the initiation of centralized electricity in the late 1800’s, there have consistently been between 1-2 billion people without access (i.e., still primarily relying on fuel-based lighting technology and fuel networks) as grid expansion has roughly paced global population. About 1.3 billion people in 2013 (2) were completely off-grid, and many ostensibly connected people in the developing world experience significant outages accumulating to 20-200+ days a year (31).

Today there is continued grid expansion with a range of projected trends in grid-based access through 2030 (which has become a benchmark year). The IEA, the most cited source, expects that over 900 million people in rural areas will remain without electricity by 2030, in contrast to only about 100 million in urban areas, with the vast majority in Sub-Saharan Africa (2). SE4ALL, using data from the IEA, expects that reaching universal access will require grid extension for all new urban connections and 30% of rural populations, with the remaining 70% of rural people gaining access through decentralized solutions (65% via minigrids, 35% via SHS and intra household, or ‘pico’ products)(2). The Global Energy Assessment by the IIASA projects a slightly higher number of unserved, with over a Billion people lacking access in rural areas in 2030, and nearly 200 million in urban zones (32). The scenario we present in Figure 3C includes grid extension supported with new policies that grows faster than population (the purple wedge) and a rapid expansion in decentralized power systems to achieve universal access to either on- or off-grid electricity by 2030.

Despite more than a century of expansion, and an emerging recognition that access to electricity constitutes a human right (33), we identify pervasive “energy isolation barriers” that people continue to experience in the context of grid-based electrification as a result of multiple dimensions of remoteness: geographic, economic, and political. Complex geography, long transmission distances, and diffuse populations restrict grid extension in poor nations to many rural areas due to high marginal cost of connection compared to expected usage (34). The economic limitations of the rural poor are reflected in their low energy consumption, struggle to pay connection fees, and challenges in procuring household wiring and appliances (35). In fact, many households and businesses in “electrified” areas lack access, even directly beneath power lines (36). Finally, centralized grid extension often requires a degree of political power that is a barrier for disadvantaged rural and urban populations with opposition, marginalized, or diffuse societal and political affiliations who are not supported by strong institutions (34, 37). People and communities without property rights may lack the stability to justify investments in fixed infrastructure, or permission from central authority to do so.
Figure 3: Two centuries of historical trends and a potential future scenario from 1830 to 2030 for electricity access in the context of technology and supporting network events and trends. In (a) the technology timeline shows watershed moments of innovation and market paradigm shifts. Panels (b) and (c) show the population with access to electricity over the time period, with (c) reflecting a potential future scenario for decentralized electricity development. Panel (d) shows a range of market penetration for ICT, going as far back as telegrams, a primary enabling technology in the spread of electric grids. Mobile phones, also shown, are the contemporary alternative to decentralized systems. The lower plot (e) shows the trend in electric light source efficacy for a range of technology including LED solid-state lighting. A full description of the data sources and analysis for this figure are in the Supplementary Material.
The Electricity Service Continuum
Recent decades have seen an emergence of a continuum of off-grid electricity systems that does not require the same supporting networks as centralized power generation and overcomes the aforementioned energy isolation barriers. Where electricity grids require installation of capital-intense fixed infrastructure to reach an affordable scale, the decentralized power network is more diffuse. There are still important hubs, like networks of manufacturing in Southeast Asia where a majority of components and integrated systems are produced at scale, but these are connected to end users by dynamic global supply chains and knowledge networks instead of fixed physical infrastructure.

While dynamo generators and arc lighting, which perform best at large scale, catalyzed the market for electric utilities, it is a range of semiconductors (stemming from the discovery of the transistor noted in Figure 3) that have been instrumental for modular decentralized power systems. High-performance, low-cost photovoltaic generation, paired with advanced batteries and controllers, provide scalable systems across much larger power ranges than central generation, from megawatts down to fractions of a watt. The rapid and continuing improvements in end-use efficiency for LED lighting (38) (e.g., see Figure 3), DC televisions (39), refrigeration (40), fans (41), and ICT (42) (a “super-efficiency trend”) enable decentralized power and appliance systems to compete with legacy equipment on a cost for energy service basis for basic household needs. These rapid advancements in basic technology supporting clean energy both on- and off-grid are furthermore predicted to continue.(38, 43, 44)

With these technological cornerstones, aid organizations, governments, academia, and the private sector are developing and supporting a wide range of approaches to serve the needs of the poor, including pico-lighting (PLS) (11), solar home systems (SHS), and community-scale micro- and mini-grids (2, 3). While these decentralized systems (and particularly PLS and SHS) are clearly not substitutes for a reliable grid connection, they each represent an important level of access until a reliable grid is available and feasible. By overcoming access barriers often through market-based structures, these systems provide incremental and often substantial increases in access to services, compared to the status quo. Table 1 is a synthesis of how the continuum of technology is often divided for analysis, and how each level in the energy stack is related to access barriers. Figure 4 shows pictograms of the systems and presents our analytical framework for assessing the cost and performance across the range of systems.
Table 1: Basic characteristics of electricity access technology options with descriptions of the typical range of generation capacity, fuel mix, services available, and the degree to which economic, geographic, and political isolation is a barrier to adoption. The descriptions are a synthesis from the authors’ experience and research.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Generation Capacity (Watts)</th>
<th>Services Available</th>
<th>Energy Isolation Barriers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incumbent technology bundle: Fuel Based Lighting, Dry cell batteries, Fee-based mobile phone charging</td>
<td>N/A</td>
<td>Lighting, Radio communication reception, Two-way mobile communication</td>
<td><strong>Economic:</strong> Very Low barrier. Day to day payments for increments of energy</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>Geographic:</strong> Low barrier. Requires distribution to remote areas through normal supply chains with some markup.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>Political:</strong> Low barrier. Gov’t and institutions can support market or hinder depending on policies.</td>
</tr>
<tr>
<td>Pico Power Systems</td>
<td>0.1 – 10</td>
<td>Lighting, Radio communication reception, Two-way mobile communication (Note: basically the same as incumbent bundle)</td>
<td><strong>Economic:</strong> Low barrier. Market-based dissemination. Retail cost $US 10 - 100</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>Geographic:</strong> Low barrier. Requires distribution to remote areas.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>Political:</strong> Low barrier. Gov’t and institutions can support market or hinder depending on policies.</td>
</tr>
<tr>
<td>Solar Home Systems</td>
<td>10 – 10^3</td>
<td>Same as above plus television, fans, additional lighting and communication, limited motive and heat power.</td>
<td><strong>Economic:</strong> Medium barrier. Market-based dissemination. Retail cost $US 75 - 1,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>Geographic:</strong> Low barrier. Requires distribution to remote areas.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>Political:</strong> Low barrier. Gov’t and institutions can support market or hinder depending on policies.</td>
</tr>
<tr>
<td>Microgrid</td>
<td>10^3 – 10^6</td>
<td>Same as above with opportunity for community-based service with higher power requirements e.g. water pumping or grain milling</td>
<td><strong>Economic:</strong> Medium-high barrier. Requires financing or investment aggregation for large capital outlay but offers relatively low marginal cost electricity to users.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>Geographic:</strong> Medium barrier. Requires critical density of population</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>Political:</strong> Medium barrier. Requires community support and local political decisions.</td>
</tr>
<tr>
<td>Regional Grid</td>
<td>10^6 – 10^9</td>
<td>Depending on the quality of connection, same as above up to a full range of electric power appliances, commercial and industrial applications.</td>
<td><strong>Economic:</strong> Medium to high barrier. Often high initial connection costs, but low cost power after connection. (Cost of power lines)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>Geographic:</strong> High barrier. Requires nearby transmissioning and distribution infrastructure.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>Political:</strong> High barrier. Depends on ministerial and departmental decisions about extension.</td>
</tr>
</tbody>
</table>
Meeting peoples’ basic lighting and communication needs is an important first step on the “modern electricity service ladder”. Eliminating kerosene lighting from a household improves household health and safety(14) while providing significantly higher quality and quantities of light. Access to recharging power suitable for mobile phones is at least 10x less costly on a $/kWh basis with electricity ($100/kWh for fees at a shop vs. ~$10 or less for the levelized cost of electricity as shown in Figure 4B). This frees income and also tends to lead to higher rates of utilization for highly valued mobile phones and other small devices.(45) Overall, the first few watts of power mediated through efficient end-uses lead to high marginal benefits in household health, education, and poverty reduction (16, 46). Beyond basic needs there can a wide range of important and highly-valued services provided by decentralized power (e.g., television, refrigeration, fans, HVAC, motor-driven applications) depending on the power level, reliability, scarcity, and power quality along with demand-side efficiency and appliance access.

Experience with the off-grid poor confirms the high value derived from the first increment of energy service—equivalent to 0.2-1 Wh/day for mobile phone charging or the first 100 lumen-hours of light—as indicated by the incumbent technology consumption-cost regimes noted in Figure 4A. Given the cost and service level that fuel-based lighting and fee-based mobile phone charging provide as a baseline, simply shifting this expenditure to a range of modern energy technology solutions could provide much better service, or in the case of PLS, similar service can be provided at significant cost savings over the lifetime of the product (typically 3-5 years) (47).

We observe a power-law inverse relationship between the unit cost and scale of electricity supply technology from pico-power to gigawatt grids. Figure 4B shows that relationship, comparing the range of costs for decentralized power across several orders of magnitude in scale. As the underlying technology and economies of scale continue to improve and shift, this relationship will likely change as well, with a reduced slope as the cost for small-scale power decreases.

The critical role of superefficient lighting for amplifying the service capabilities of power systems is highlighted in Panel 4C and is indicative of similar trends across other appliance types. It shows how a hypothetical person who consistently invests $100 per year for lighting shifts from an energy “investment” of over 2000 Wh per day (as liquid kerosene fuel) for 100 lm-hr of lighting service to 20,000 lm-hr with a grid connection and incandescent bulb or 100,000 lm-hr with high-efficacy LED lighting. LED lighting functionally enables off-grid pico-power systems to offer the rural poor roughly the same cost performance for lighting service as grid power with incandescent lighting, in spite of higher effective unit costs for electricity, and with an order of magnitude lower energy requirements (47). Reframing kerosene lighting as an appliance shows how much of the improvement in service achieved by electrification derives from end-use rather than generation efficiency.

Mirroring the early development of electric utilities, improvements in underlying technology systems for decentralized power are also being combined with new business models, institutional and regulatory support, and information technology systems(48). Historically (and presently in
many cases), the non-technical barriers to adoption have been as much, or larger, impediments to widespread adoption of off-grid electricity. A lack of appropriate investment capital (both early-stage and growth capital) hampers the establishment and expansion of private sector initiatives (48-50). Furthermore, complex and often perverse policy environments impair entry for clean technologies and entrench incumbent systems (e.g., subsidies for liquid lighting fuels that reduce the incentive to adopt electric lighting(51)). Finally, the prevalence of imperfect or inaccurate information about quality can lead to market spoiling(52) in early-stage markets where buyers’ understanding of and experience with alternatives to incumbent lighting technology is limited.

Significant and rapid proliferation of off-grid solar systems has nonetheless occurred recently in spite of these barriers, as shown in Figure 5, where we demonstrate the growth trajectory of commercial sales supported by three particular approaches from 2004-2014. These include: country-targeted support like the IDCOL program (Solar home system financing and subsidy program in Bangladesh) (1), global market transformation like Lighting Africa (2), and next-generation pay-as-you-go solar businesses like M-KOPA that use mobile money and new delivery models for end-user asset financing (3). With 10’s of millions of households using off-grid power systems, the market has clearly moved past pilot scale. The growth suggested by the early market is consistent with other rapidly expanding technology systems (e.g., mobile phones) and supports the potential future scenario shown in aggregate in Figure 3C, with rapid expansion in household and community-scale decentralized power.

In Figure 4 E-F we show the payment and service dynamics for the off-grid systems highlighted in Figure 5 along with two other avenues for access. One of the others is a government-supported minigrid project serving a remote community in Bhutan that is powered by a micro-hydroelectric system and includes smart grid elements that prevent brownouts by encouraging peak load shifting, improving service quality(53). Another is the national electricity grid in Mexico, which provides nearly universal grid access. It is notable that across these systems of vastly different scales the day-to-day price for service is relatively similar (all but the heavily-subsidized minigrid). Financing for off-grid household solar and community-scale power shrinks or eliminates an often prohibitively high initial cost and allows users to access electricity with payment streams more similar to incumbent kerosene and phone charging payments (or to those experienced by people with access to central grids).
Figure 4: Five views on the continuum of electricity access based on real-world system operations. Panel (a) shows the annual and (b) unit costs of electricity. The incumbent options (fuel-based lighting and fee-based charging) are included for reference, with fuel-based lighting in terms of lower heating value for typical fuel consumption ranges (12) fuel prices (54) with ±50% bounds to account for variation. Panel (c) shows the implications of superefficient lighting for a given level of spending over the technology continuum, with the unit cost of electric lighting at a given electricity consumption level (a proxy for system scale) based on regression in panel (b). The service for fuel-based lighting is displayed again as an orange rectangle, with bounds from uncertainty in fuel price and flame efficacy (0.03 to 0.05 lm/W). System pictograms are in panel (d). Panels (e) and (f) show the cost structure and electricity provided for illustrative examples: 5 Watt solar pico-power system in Kenya (with and without pay-as-you-go financing), 50 Watt solar home system in Bangladesh, 25-30 kW micro-hydro minigrid serving 90 households in Bhutan with heavy price subsidies, and the national electric grid for Mexico. The data sources and assumptions are in Supplementary Material.
Figure 5: Sales of household off-grid systems as reported by organizations active in market-based distribution. The log axis shows similarities in early growth rates between IDCOL, a solar home system financing program in Bangladesh, the Lighting Africa program, a World Bank Group market transformation effort, and M-KOPA, a pay-as-you-go solar business in Kenya.

The Information-Energy Nexus

Reliable and accurate information is critical for building sustainable energy systems, as it supports decisions about investment and management for infrastructure and technology and can help overcome market failures(55, 56). Access to electricity specifically, either through the grid or off-grid power, requires a high degree of coordination (of grids and consumer-goods markets) that lends itself to information and communications technology (ICT) applications in support of information provision. On the grid, there are new business models for aggregating demand response and managing investments in clean energy that require increasing connectivity. Coordination and control of fast-changing grids with high penetrations of renewable power is a paramount need for achieving climate goals. Similarly, the rapid emergence of global wireless communication networks and widespread access to mobile phones in the developing world (18) is a new and important supporting system for decentralized power. Targeted and well-designed “killer applications” of information technology hold the promise to accelerate the development of decentralized power systems and increase energy access for the global poor.

Pay-as-you-go (PAYG) is a good example of how ICT enables new strategies for financing and managing energy systems off the grid. PAYG is a combination of hardware and software systems that typically rely on mobile phones as a platform for making payments (or verifying the transfer of money) and most include a cut-off switch in the system hardware that prevents use when fees or loan payments have not been completed(57) (e.g., the MKOPA system highlighted in Figure 4 E). This reduces the transaction costs for providing small loans, and essentially passes retail working capital finance on to the consumer. The payment stream for PAYG off-grid power is more similar to the typical expenditures for traditional fossil or biomass fuels being replaced (and to ongoing costs for grid power)(58). This approach to financing fits peoples’ ability and willingness to pay in the context of uncertainty and careful budgeting of scarce cash.
Some systems include remote monitoring features, enabling better knowledge about user behavior and the performance of decentralized devices.

ICT is also a critical feature for supporting the supply chains and maintenance networks that connect consumers with producers of off-grid energy devices and systems. Supply chain management and intra-chain information sharing and payments are important features of energy access networks as much as they are for many other products (60, 61). By enabling information to flow much more quickly and reliably it is possible to set up vertically integrated supply chains that can be monitored and controlled, a key feature of many successful early efforts at pico-power deployment (62).

Remote monitoring and analytics of off-grid power systems can be enabled when there are systems for collecting and transmitting system metrics and performance through ICT channels like PAYG. An example application of sensing and control platforms is more effective monitoring and maintenance to address that common barrier to durable energy access across all decentralized modern energy systems, whether solar home systems, lighting, or improved stoves. The value in ICT can be amplified in regions where electronic repair or troubleshooting capacity levels are low, or in the early period of technology adoption when the density of systems is limited. There are numerous successful cases of the use of GSM enabled sensors, mobile issue reporting platforms, and remote management systems that reduce costs, improve technician response times, enhance overall service quality, reduce system outages and increase project success rates (63).

Understanding system dynamics and controlling devices on- and off-the grid will also require new ICT tools. An early example of off-the-grid responsive demand is the GridShare pilot project in Bhutan (shown as an example in Figure 4). This project successfully reduced the incidence of brownouts by 92% with load shedding devices installed and tested collaboratively with a small community that previously overloaded their microhydro generator during cooking times with electric rice cookers(53). With ICT, decentralized electricity systems can be converted into powerful data-generating processes for guiding management, policy, and investment decisions.

Information and electricity systems provide mutual support. Not only do information technologies facilitate the expansion and operation of energy systems, but many of the highly valued electricity services like mobile communications, radios, and lighting are fundamentally about getting access to information (in the case of light, real-time information about one’s surroundings or the content of visual media). An understanding of the relationships between these linked systems and how people interact with and through them is vital for supporting investment in, and smart management for decentralized and diffuse systems that span the off- to on-grid energy continuum.

Universal Access and Climate Stabilization

Vast differences in energy access between the rich and poor are a fundamental injustice. While a great deal of international attention is rightly placed on addressing climate change, in this
concluding section we argue that increasing energy access can reduce inequality in access and simultaneously contribute to reducing climate pollution, particularly in the short term through reductions in black carbon emissions (15).

Our argument is based on a simple model of technology transition applied to Kenya household expenditure data from 2005-2006 (KIHBS, n=13,430 households)(64). In the analysis we calculate the expected effect of households switching from kerosene to either off- or on-grid access for lighting service, informed by the findings described previously in this paper. The model results in estimates for the GHG intensity of lighting (including accounting for embodied energy in the manufacture of off-grid solar lighting), equality in the service provided, and financial requirements of each technological option. We assume that households using kerosene for lighting maintain their current spending level and shift expenditures completely to either off- or on-grid electricity. We chose this simple and somewhat extreme example to simulate a full transition in spending on lighting from improved efficiency, while in reality we expect that in response to vastly improved efficiency, individuals would reallocate savings to much broader categories of consumption. (65) The two scenarios present paths for approaching universal access: one models the expected characteristics of a complete transition to off-grid power using current system costs; the other explores a complete transition to grid power, with the spending applied to available electric utility rates. Details on the assumptions and methodology are available in supplementary materials.

Figure 6 summarizes the results of the technology transitions estimates. Panel 6A presents the climate implications for different levels of electricity access in the scenarios we used. In the status quo case, if one ignores the role of black carbon (BC), it appears that kerosene users induce substantially lower emissions than those connected to the grid. However, when the effects of BC are accounted for (using 100 year Global Warming Potentials), climate forcing from households using kerosene lighting appears nearly ten times higher than the typical grid-connected household. Shifting away from fuel-based lighting to either on- or off-grid power is thus a significant mitigation opportunity.

Improved access to electricity also leads to drastic improvements in equality of access to service as shown in Panel 6b, which shows variations in access in terms of Lorenz curves and GINI coefficients.(66) The intrinsic inequality in prosperity (as measured by total expenditure) in the country is magnified by the fact that the poor must spend a higher fraction of their income on energy (see Panel 6c that indicates the median fraction of spending is roughly double for users of kerosene than those with grid access). This spending is mediated through technology systems that result in different levels of available service. In the status quo scenario, the service distribution is highly unequal, with a GINI of 0.95. Poor people without electricity access pay
more (as a fraction of their income) for vastly inferior levels of service. Shifting from kerosene to off-grid power leads to substantial improvements in equality but is still more unequal than national energy spending levels since the relationship between consumption and unit cost of service is regressive through the continuum of off-grid power. A wholesale shift to grid electricity actually results in higher equality in energy service than the baseline national spending, because retail electricity rates are progressive with costs that increase with use. This analysis clarifies how off-grid technology is an important intermediate step to improve service for those who cannot access the grid due to pervasive barriers in access.

Stepping from kerosene to off-grid power before attaining grid access could have benefits that extend past grid connection. Experience with superefficient appliances and solar energy systems may prove to be valuable for encouraging efficient use of grid-based power if user (and institutional) experience with LED lighting, advanced battery storage, and photovoltaics meet or exceed their expectations and build trust. Those who keep off-grid power systems in place as an ongoing complement to grid power will have battery-backed lighting and power systems that add resiliency for basic services in the face of often-unstable grids in the developing world.
Figure 6: Results from a simple model of electricity / lighting technology climate impacts and adoption dynamics in Kenya. The base data are from the Kenya (KIHBS 2005-06, n = 13,158). (a) shows the expected range in GHG emissions induced by household electricity or lighting use, with boxplots demarcated at the 25th, 50th, and 75th percentiles and whiskers to 1.5x the inter-quartile range and outlier points. The status quo scenario shows emissions with and without accounting for BC emissions from open wick lamps that comprise 55% of the lamps in use. (b) shows the levels of inequality inherent in service measures (peak lumen-hours available) and expenditure measures that reflect the broader inequality in the society with Lorenz Curves and GINI coefficients to quantify degrees of equality in the spirit of Jacobson, Milman (66) (c) shows the fraction of expenditures devoted to kerosene and electricity in the status quo scenario for primary users of both. The inset scatterplot shows the poor tend to spend a higher fraction of income on energy. (d) shows the implied number of years of household savings at a 10% of expenditure rate to accumulate cash for upfront payments for grid and off-grid power.

Panel 6d shows the high hurdle of up-front costs of systems for which the poor have demonstrated a willingness to pay, based on the kerosene expenditures reported in the survey. The reality we observe in the field is that many people choose to invest in systems that offer lower service levels than what would be affordable with perfect financing. Therefore, access to consumer capital for off-grid power, particularly through ICT-supported PAYG, will be a necessary element for reaching scale. The electricity purchased through utilities on the grid inherently includes financing that is obtained on customers’ behalf, allowing monthly payments for service, and expansion of off-grid systems will require the same financial support.
In principle many off-grid households and businesses are close enough to power grid transmission and distribution lines to allow for interconnection, but face steep cost barriers related to the fixed cost of installing additional service drops, poles, and meters that are inherently tied to that location. Compared to the median investment required for cash sales of off-grid power, the full cost of grid connections in Kenya requires twice, to many times more, the liquid capital (see Figure 6d for a comparison of median savings periods required). For households farther afield, or for renters who face principal-agent problems, the challenge to grid access is amplified further. There are likely opportunities to reduce these barriers to grid-based service through aggregation of community connections or through mini-grids that can achieve economies of scale in remote areas. These should be pursued in parallel with off-grid decentralized power options that, while providing lower power levels, often have greater flexibility in deployment and scalability. Past experience with grid expansion and the current mix of approaches suggests that a diverse suite of public, private, and hybrid efforts that meet the needs of particular contexts will be most successful at rapidly deploying these new technology systems.

Taken together, our observations from the field combined with analysis of historical and contemporary datasets shows the emergence of a unique and new opportunity to simultaneously improve equality in access to energy services and reduce GHG emissions through the rapid expansion of off-grid and grid-based connections to electricity systems. With a foundation of super-efficiency and carbon-free generation, supported by new ICT connectivity and applications, expanding access through decentralized power systems could have radically different climate and equity impacts than the incumbent system, challenging the conventional knowledge held by some that one must choose between progress on energy access or climate.

Chapter 1 References


Chapter 1 Supplementary Materials

Decentralized energy systems for clean electricity access

Peter Alstone, Dimitry Gershenson, and Daniel M. Kammen (2014)

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**SOM D: Figure 6**

References
The response thus far to the multi-dimensional problems of global climate and poverty has been driven primarily by multilateral institutions (e.g., the United Nations Framework Convention on Climate Change and the United Nations Development Programme) and articulated in large consensus reports like the IPCC Assessments of Climate Science and Human Development Reports. In assessing progress and planning future action, there is a critical role for global metrics, for both climate and poverty. While climate pollutants lend themselves to direct measurement (albeit with continuing improvement in the understanding of atmospheric chemistry, forcing, and sources), poverty, like other social issues, is less straightforward to measure. The current commonly used broad indices are the Human Development Index (HDI) and the Millennium Development Goal indicators from the United Nations but there are other measures in parallel and in development that support a richer picture of development. The Human Development Index (HDI) was developed by the UNDP to provide a multi-objective metric to track progress of poverty alleviation through a synthesis of health, education, and living standards. The HDI was expanded upon with the introduction of the Millennium Development Goals, which include eight targets and 20 indicators. The MDGs present a multidimensional view of improving human development, from measures of literacy to gender equality and infant health. In Figures 1 and 2 we show how these indices are related to electricity access.

The electricity access data are from years 2000, 2002, 2004, 2007, 2009, and 2010 as reported in the IEA World Energy Outlook Reports (2002-2012). The Human Development Index data are from the UNDP for years 2000-2010. Missing years that align with the electricity access dataset are estimated based on a linear fit from the two closest years. The Millennium Development Indices data are from DevInfo. No missing data were replaced in the MDG dataset. For the Gender Parity Index data (2A), 14 values above 2 (i.e., twice as many women as men) were discarded as outliers. Each plot in the MDG panels shows points from the same country in the same year.

The lines of best fit and coefficients of determination ($R^2$) were calculated with simple linear models from package:stats in the R statistical programming language. The sample sizes for the data are 1: 762, 2A: 263, 2B: 206, 2C: 117, and 2D: 168. Regression results for the linear models are displayed below but should not be interpreted as arguments for a statistically causal relationship. The “$R^2$” coefficients of determination for the relationships range from approximately 0.5 to 0.75, suggesting that about half the
variation in human development can be explained by electricity access or some correlate of access but that other factors are also important determinants.

Table S1: Regression Tables for Figures 1 and 2

**Figure 1 Regression Table**

<table>
<thead>
<tr>
<th></th>
<th>hdi</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>HDI</strong></td>
<td></td>
</tr>
<tr>
<td><strong>elec</strong></td>
<td>0.004***</td>
</tr>
<tr>
<td>(0.0001)</td>
<td></td>
</tr>
<tr>
<td><strong>Constant</strong></td>
<td>0.279***</td>
</tr>
<tr>
<td>(0.008)</td>
<td></td>
</tr>
<tr>
<td><strong>N</strong></td>
<td>762</td>
</tr>
<tr>
<td><strong>R2</strong></td>
<td>0.670</td>
</tr>
<tr>
<td><strong>Adjusted R2</strong></td>
<td>0.670</td>
</tr>
<tr>
<td><strong>Residual Std. Error</strong></td>
<td>649.112 (df = 760)</td>
</tr>
<tr>
<td><strong>F Statistic</strong></td>
<td>1,543.156*** (df = 1; 760)</td>
</tr>
</tbody>
</table>

**Notes (apply to all regression tables):**

***Significant at the 1 percent level.
**Significant at the 5 percent level.
*Significant at the 10 percent level.

**Figure 2A Regression Table**

<table>
<thead>
<tr>
<th></th>
<th>mgd.15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gender Parity Teriary Education</td>
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</tr>
<tr>
<td><strong>elec</strong></td>
<td>0.008***</td>
</tr>
<tr>
<td>(0.001)</td>
<td></td>
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<tr>
<td><strong>Constant</strong></td>
<td>0.413***</td>
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<tr>
<td>(0.040)</td>
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<td><strong>N</strong></td>
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<tr>
<td><strong>R2</strong></td>
<td>0.495</td>
</tr>
<tr>
<td><strong>Adjusted R2</strong></td>
<td>0.493</td>
</tr>
<tr>
<td><strong>Residual Std. Error</strong></td>
<td>0.293 (df = 250)</td>
</tr>
<tr>
<td><strong>F Statistic</strong></td>
<td>245.252*** (df = 1; 250)</td>
</tr>
<tr>
<td>Regression Table</td>
<td></td>
</tr>
<tr>
<td>------------------</td>
<td></td>
</tr>
<tr>
<td><strong>Figure 2B</strong></td>
<td></td>
</tr>
<tr>
<td>____________________________</td>
<td>mdg.11</td>
</tr>
<tr>
<td>Proportion of grade 1 who complete Primary Ed.</td>
<td></td>
</tr>
<tr>
<td>__________________________________________________________________________</td>
<td></td>
</tr>
<tr>
<td><strong>elec</strong></td>
<td>0.421***</td>
</tr>
<tr>
<td><strong>Constant</strong></td>
<td>46.706***</td>
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<td><strong>N</strong></td>
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<td><strong>R2</strong></td>
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<td><strong>Adjusted R2</strong></td>
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</tr>
<tr>
<td><strong>Residual Std. Error</strong></td>
<td>11.184 (df = 204)</td>
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<tr>
<td><strong>F Statistic</strong></td>
<td>362.397*** (df = 1; 204)</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Figure 2C</strong></td>
<td></td>
</tr>
<tr>
<td>____________________________</td>
<td>mdg.1</td>
</tr>
<tr>
<td>Proportion of people living on &lt;1/day (PPP)</td>
<td></td>
</tr>
<tr>
<td>__________________________________________________________________________</td>
<td></td>
</tr>
<tr>
<td><strong>elec</strong></td>
<td>-0.571***</td>
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<td><strong>Constant</strong></td>
<td>60.346***</td>
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<td><strong>R2</strong></td>
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<tr>
<td><strong>Adjusted R2</strong></td>
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<td><strong>F Statistic</strong></td>
<td>263.641*** (df = 1; 115)</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Figure 2D</strong></td>
<td></td>
</tr>
<tr>
<td>____________________________</td>
<td>mdg.21</td>
</tr>
<tr>
<td>Maternal Mortality Ratio</td>
<td></td>
</tr>
<tr>
<td>__________________________________________________________________________</td>
<td></td>
</tr>
<tr>
<td><strong>elec</strong></td>
<td>-5.688***</td>
</tr>
<tr>
<td><strong>Constant</strong></td>
<td>606.969***</td>
</tr>
<tr>
<td><strong>N</strong></td>
<td>168</td>
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<tr>
<td><strong>R2</strong></td>
<td>0.669</td>
</tr>
<tr>
<td><strong>Adjusted R2</strong></td>
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</tr>
<tr>
<td><strong>Residual Std. Error</strong></td>
<td>135.536 (df = 166)</td>
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<tr>
<td><strong>F Statistic</strong></td>
<td>336.185*** (df = 1; 166)</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
As a point of interest and to support the narrative in the paper we also use the data to show relationships between electricity consumption (kWh/person-year) and human development index similar to the relationship originally suggested by Goldemberg, Johansson, Reddy and Williams ³. This is displayed in Figure S1.

![Figure S1: The relationship between electricity consumption and human development index based on country-level data similar to Figure 1 in the main text. These representations use electricity consumption (rather than access levels) for the abscissa with continuous (a) and logarithmic (b) scales.](image-url)
In the main text we highlight four aspects of the MDG in panels A-D of Figure 2. The other MDG aspects with meaningful data available are presented here for completeness for the interested reader. Note that in most cases the “expected” relationship between energy access and human development goals holds, albeit with some variation in the strength of the relationship and support of data.

Table S2.1-8: MDG Indicators and Electricity Access Plots

**MDG1: ERADICATE EXTREME POVERTY AND HUNGER**
**MDG2: ACHIEVE UNIVERSAL PRIMARY EDUCATION**

2.01 Net enrolment ratio in primary education (NER)

2.02 Proportion of pupils starting grade 1 who reach last grade of primary

2.03 Literacy rate of 15–24 year-olds

**MDG3: PROMOTE GENDER EQUALITY AND EMPOWER WOMEN**

3.01 Gender Parity Index in primary level enrolment

3.01 Gender Parity Index in secondary level enrolment

3.01 Gender Parity Index in tertiary level enrolment
MDG4: REDUCE CHILD MORTALITY RATES
MDG5: IMPROVE MATERNAL HEALTH

5.01 Maternal mortality ratio (MMR)

5.02 Births attended by skilled health personnel

5.03 Contraceptive prevalence rate (CPR)

5.04 Adolescent birth rate

5.05 Antenatal care coverage for at least one visit (ANC)

5.05 Antenatal care coverage for at least four visits

5.06 Unmet need for family planning
MDG6: COMBAT HIV/AIDS, MALARIA, AND OTHER DISEASES

6.01 People living with HIV

6.05 Proportion of population with advanced HIV infection with access to antiretroviral drugs

6.07 Proportion of children under-five sleeping under insecticide-treated bednets

6.08 Proportion of children under-five with fever who are treated with appropriate anti-malarial drugs

6.09 Death rate associated with tuberculosis

6.09 Incidence of tuberculosis

6.09 Prevalence of tuberculosis

6.10 Tuberculosis detection rate under DOTS

6.10 Tuberculosis treatment success rate under DOTS
MDG7: Ensure Environmental Sustainability

7.01 Land area covered by forest

7.02 Carbon dioxide emissions

7.02 Carbon dioxide emissions per capita

7.03 Consumption of all ozone-depleting substances

7.05 Proportion of total water resources used

7.06 Proportion of terrestrial and marine areas protected to total territorial area

7.08 Proportion of population using an improved drinking water source

7.09 Proportion of population using an improved sanitation facility

7.10 Proportion of urban population in slum areas
MDG8: Develop a global partnership for development

8.04 ODA received by landlocked developing countries as a proportion of their GNI

8.06 Developed country imports from developing countries, admitted duty free

8.06 Developed country imports from the LDCs, admitted duty free

8.12 Debt service as percentage of exports of goods and services and net income from abroad

8.14 Telephone lines

8.15 Cellular subscribers

8.16 Internet users
SOM B: Figure 3 Details

**Data Preparation**
The table below summarizes the data used to develop a time series picture of development and electricity grid expansion.

**Table S3: Data and Sources for Figure 3**

<table>
<thead>
<tr>
<th>Code</th>
<th>Title</th>
<th>Data File</th>
<th>Description</th>
<th>years used</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>mad. pop</td>
<td>Maddison Population Data</td>
<td>maddison-pop.csv</td>
<td>Historical population 1-2008 AD</td>
<td>1-1950</td>
<td><a href="http://www.ggdc.net/maddison-project/home.htm">http://www.ggdc.net/maddison-project/home.htm</a></td>
</tr>
<tr>
<td>mad. gdp</td>
<td>Maddison GDP data</td>
<td>maddison-gdp.csv</td>
<td>PPP Adjusted GDP (SGK 1990) 1-2008 AD</td>
<td>1-2008</td>
<td><a href="http://www.ggdc.net/maddison-project/home.htm">http://www.ggdc.net/maddison-project/home.htm</a></td>
</tr>
</tbody>
</table>
Step 1: Data cleaning
1. Headers renamed for country and year data.
2. Comma separated values files cleaned and combined.
3. Country names were unified using algorithms in Open Refine.

Step 2: Combining Data into a Time Series Table (this and subsequent analytical steps in R)
We created a yearly time series table from 1830-2030 for counties with data in our source datasets and added data to it in a stepwise fashion. The data sources cover varying years and geographic regions and were combined with priority given to data with better coverage in any given year. We add region labels to the data based on World Bank Group region classifications (as explained here: http://data.worldbank.org/about/country-classifications).

Step 3: Interpolating Population
We interpolate (linear) for population, which has good support over the time period.

Step 4: Estimating country-level electricity access
We use a three–step process to “fill in the gaps” in the historical record for electricity access:
1. Interpolate inside the support of the data for countries with several (>4) datapoints in the pre-1990 period (many have good coverage in the 90’s and 2000’s).
2. Replace any missing values that can be estimated with a linear regression model to for electricity access post-1950 during which time there is sufficient data. The model uses ordinary least squares regression with the formula “elec ~ region * income.class * gdp.per.capita * year * year^2 * year^3”. While many of these estimates have limited support the aggregate effect is to add reasonable estimates for missing country-level electricity access can be aggregated into global averages if one assumes that the counties with raw data are representative of the regional / global average.
3. For values that are still missing (pre-1950 and for countries without regression support) use linear interpolation to fill in all missing values. This results in first-order estimates for country-level electricity access that are reasonable to use for inputs to global aggregate results but have large uncertainty and poor functional form on the country level. We assume there was zero access to electricity before 1882 (in practice there was off-grid power from batteries and isolated plants at key industrial and other facilities but essentially no individuals had electricity access in a meaningful way).

Step 5: Summing and Normalizing
We sum the on-grid population and total population globally to arrive at estimates of the global access picture and calculate global electricity access and off-grid population in each timestep. There are divergences at various times in the electricity access estimates because of multiple datasets with slightly different coverage on the country-level. To account for these we use a natural spline smoothing technique to reduce stepwise divergence in the electricity access fraction data. Additionally, we use a Bass Diffusion model for the first 23 years of electricity operation (1882-1905) with a q:p ratio of 15 to link pre-access 1882 to the estimate in global access for 1923. We use linear smoothing to link our estimates with the known global benchmark of 81% access in 2010 (from the IEA). The total global population estimates are scaled so the totals match well-agreed totals for overall population, and we re-estimate the on- and off-grid population estimate globally based on the average electricity access rate is the same as in the base
data. This normalization requires the assumption that the overall regional / global electrification rate is the same in areas with missing data as in those with complete datasets.

**Step 6: Adding Scenarios**
We present a future scenario from 2010 to 2030. The population is based on the mean of the medium, low, and high fertility scenarios from the UN. The fraction of people with electricity in 2030 is taken from the “New Policies” Scenario from the IEA World Energy Outlook, with a linear interpolation between the historical data and the forecast.

**Step 7: Technology Wedges**
There are three technologies that fill the gap between the current extent of the grid and the expected off-grid population in a “no action” scenario. Without action (i.e., with no grid extension and no new connections to the grid—not an expected scenario but a baseline) the number of people off the grid grows with population. There are three technologies that could fill the gap:

1. **Electric grid:** We take the IEA “New Policies” Scenario for electrification, which estimates that ~900 Million people will be without a grid connection in 2030. There is a linear estimate of the trend for electrification between the current day and 2030.

2. **Minigrids and Microgrids:** We use a Bass Diffusion model ("s-curve of adoption") in the form shown below to develop a potential scenario for filling up to 30% of the unelectrified gap. The parameters are $m=30\%$, $p=0.008$, $q=0.25$.

3. **Pico-products and home systems:** We use a Bass Diffusion model ("s-curve of adoption") in the form shown below to develop a potential scenario for filling up to 70% of the unelectrified gap. The parameters are $m=70\%$, $p=0.005$, $q=0.45$. The resulting trend, if it is interpreted as the number of products sold, is in alignment with the current (albeit nascent) trends in the off-grid lighting market.

### Bass Diffusion Model

$$S(t) = m \frac{1 - e^{-(p+q)t}}{1 + \frac{q}{p} e^{-(p+q)t}}$$

*Where:*

- $S(t)$ = Market share at time $t$
- $m$ = Maximum market share
- $p$ = “innovation parameter”
- $q$ = “imitation parameter”
- $t$ = number of time periods past introduction

**Step 8: Supporting Technology:**

The technology timeline is based on well-known historical information.
There are several data sources we use directly for plotting, without any modification:

<table>
<thead>
<tr>
<th>Data Source</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Telegraphs</td>
<td>7</td>
</tr>
<tr>
<td>Fixed-line telephones and mobile phones</td>
<td>8</td>
</tr>
<tr>
<td>Incandescent and Fluorescent Bulb Efficacy Trends and Historical LED Efficacy (up to 2007)</td>
<td>9</td>
</tr>
</tbody>
</table>

**Step 9: Forecasted LED Trend:**

We take the yearly peak product from the US Department of Energy Caliper LED lighting testing database and create a linear trend to estimate the future trajectory of LED lighting efficacy. The eventual efficacy in 2030, approximately 250 lm/W, is not close enough to the theoretical limit for white light of good quality (about 400 lm/W) to be unreasonable in terms of technical feasibility, particularly in the context of past experiences with semiconductor learning curves.

**Note:** The photographs in the timeline are all in the public domain and were obtained from Wikimedia Commons:

http://commons.wikimedia.org/wiki/File:Monocrystalline_silicon_in_solar_cells.jpg
http://commons.wikimedia.org/wiki/File:The_First_Transistor ever_made built in 1947 Bell_Labs.jpg
http://commons.wikimedia.org/wiki/File:Edision_PowerPlant_Pearl_Street_NYC.jpg
http://upload.wikimedia.org/wikipedia/commons/a/ae/AhotwSolar-powered_lamp_and_charger.JPG

**Step 10: Combining elements and layout:**

We use Adobe Illustrator to combine elements of the integrated figure without changing the information content.

**SOM C: Figure 4 Details**

Household energy expenditures and service levels in emerging countries have been a topic of interest for many years \(^{10-12}\). For the purposes of this paper we used a variety of data sources to compose Figure 4, which are outlined in Table S4 below. Some of the projects were considered failures, or unsustainable, by case study authors, however we believe that the prices still provide an accurate representation of levelized costs for decentralized power generation currently. For each case of failure, there were diverse reasons that are common for decentralized installations, including limited capacity, poor tariff collection practices, inappropriate system sizing, etc. \(^ {13} \). The pico-solar data come from laboratory measurements conducted by the Lighting Africa program and provided to use in aggregate form in Table S5 (and available as are the other data from our research archive).
It is common for people in the developing world to travel long distances and pay ~$US 0.25 for a phone charge at a shop with power available, an effective rate of about $60/kWh for electricity, i.e. over 100 times the typical rates for on-grid power \(^{14}\) and similar in scale to purchasing dry-cell batteries for powering radios and small devices. For mobile phones we assume each household charges 2-4 phones per week and pays the central estimate of $60/kWh ±50% (with consumption of batteries implicitly included in the range of consumption).

People who use fuel-based lighting are essentially locked into low-efficacy open flames for converting energy to light; those with access to electricity have a range of better options. Using LED lighting even with small scale systems (in the range of pico-power) can result in similar levels of lighting as grid-based electricity with incandescent lighting.

Grid-connected electricity tariffs were collected from various case studies. The majority are from the period of 2003-2013, and accurately represent today’s tariffs in the documented countries. To estimate household energy consumption for grid-connected populations, we use the IEA World Energy Outlook 2012 Energy for Development Database \(^5\). The Database presents 80 normalized estimates for residential electricity per capita in the developing world, with a cap at 0.1 tonnes of oil equivalent (1,163 kWh/year). The process we used to extract estimates was:

1. Discard any normalized values equal to one, which indicates the cap is met or exceeded. One value was discarded (Lebanon).
2. Denormalize the remaining values, translating the linear 0-1 estimate to 0-1,163 kWh/pp-year.
3. Divide the “per capita” electricity consumption by the electrification rate to estimate a “per user” electricity consumption—representing the level of consumption among those with access.
4. Multiply by household size (assume uniform size of 5) and divide by 12 months/year to estimate monthly household consumption (kWh/hh-month).

**Table S4: Data and Sources for Figure 4**

<table>
<thead>
<tr>
<th>Year</th>
<th>Power Level (kwh/month*household)</th>
<th>$/Kwh</th>
<th>System Type</th>
<th>Generation Technology</th>
<th>Source</th>
<th>Country</th>
</tr>
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<td>Solar</td>
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<tr>
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<td>Year</td>
<td>Value</td>
<td>Multiplier</td>
<td>Energy Type</td>
<td>Grid Mix</td>
<td>Country</td>
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<td>Household</td>
<td>Solar</td>
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Table S-5: Aggregate performance and price data for pico power products, from the Lighting Africa program. These data are anonymous and aggregated so no individual product can be identified.

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The base data are from the Kenya Integrated Household Budget Survey (KIHBS 2004-05, n = 13,158). Expenditures on kerosene (primary source for ~74% of the households) and electricity (primary source for ~16% of the households) are analyzed in a set of scenarios for technology impacts and transitions.

Two basic scenarios are modeled: “Kero->OffGrid” - all current users of kerosene shift that expenditure perfectly to off-grid power with characteristic unit costs and performance levels determined by placing that expenditure in the the continuum observed in Figure 3, which assumes perfect financing. “Kero->Grid” - users instead are able to connect to the national grid at “domestic” i.e. household retail rates and similarly shift their full spending stream to electricity payments (ignoring that many people using kerosene are not co-located with the grid or may face other barriers, and not accounting for the connection fees or appliance purchase requirements for grid access, only the ongoing payments).

More details on the model are included in the code notebook appended to this supplementary material.

References (Chapter 1 Supporting Material)


**Power Markets and Institutions Beyond the Grid**

Across the globe, investment in clean energy technology is needed on an unprecedented scale to achieve the aggressive climate goals required to mitigate global change (22) and provide equitable service. In Chapter 1 we showed it is possible to simultaneously make progress on both fronts with off-grid solar, and as ICT and renewable power transform the off-grid sector, centralized power systems around the world are also poised at the edge of these two separate but interrelated technological revolutions.

A diverse set of stakeholders including the public and private sector makes decisions that contribute to the architecture and operation of the electric power system on- and off-grid. Figure 1 illustrates the range of scale over time for actions taken to build and operate the global system. Users of off-grid power (and decentralized energy systems like rooftop PV or electric vehicles) take actions to purchase and use their devices on day-to-month timescales, and may operate them for years and up to a generation. The investments they make will result in persistent changes to the underlying structure of the hardware in the energy system. Operating and making use of the evolving energy system is the joint task for people and the growing set of hardware and software machines that control the power system. Given the pace of progress required on clean energy to avert the worst effects of climate change (significant reductions in carbon pollution are now needed in just over a generation(23)), it is imperative that institutional frameworks are used to support and guide large-scale shifts in the industrial economies and markets of the world (e.g., markets for electronic goods like off-grid solar and electricity systems).

![Figure 1: Timescales for the electricity system actions and decisions. Adapted from von Meier (2012), (24).](image)

A unique challenge for managing grid-based electric power systems from a policy and economic perspective (not to mention technically) is that the systems are typically large enough to require coordination of diverse generation and demand resources, but unlike most situations where markets and administrative purchases link large groups of buyers and sellers there is nearly zero
lag in time between production and consumption. Thus cooperation on a massive scale is required to maintain the stability of electric power grids, and critical policy debates and regulatory transformations to enable a “next generation grid” are underway (e.g., *Renewing the Energy Vision* in New York and a range of distributed energy resource rulemakings at the California Public Utilities Commission). Similarly, there are new challenges in supporting off-grid solar energy systems that are distributed along with other fast-moving and durable consumer goods markets from global factories to the edge of decentralized energy service delivery networks, leveraging increasingly widespread but fragmented information technology systems.

In the Chapters that follow this section, we explore the market, policy, and institutional dynamics of fast-growing PAYG solar enterprise networks with a focus in Kenya. Our work is based on extensive market research in at the retail level in Kenya in partnership with the World Bank Group’s Lighting Global program and supported with end-user research and structured interviews across a diverse set of actors in the supply chain. But first, for background, it is helpful to look back at the early history and contemporary issues in grid expansion and linked information-energy systems to illuminate dynamics between private enterprise and public interest support for growing energy infrastructure networks.

**HISTORICAL AND CONTEMPORARY NETWORKS OF POWER AND TECHNOLOGY**

The early expansion and development of electric power grids in developed areas like much of the Americas, Europe, parts of Asia, and cities around the world highlights the limitations to centralized technology systems for reaching the margins and also raises questions about how the regulatory structure should (or will) evolve for decentralized energy.

Early electric power grids were run by the enterprising entrepreneurs of their day, branching out from the early-adopting coastal hubs of New York, Paris, and London. Growing into multinational private enterprises, utility operators opportunistically followed existing links of trade and capital to quickly electrify the world’s cities and factories, using mainly standalone power stations and mini-grids. Hausman et al.’s work on mapping the evolving business and institutional networks of power systems shows they developed quickly to serve the needs of urban and industrial users that concentrated demand and ability to pay for electric service, combining to create both smaller and higher return investments in transmission and distribution infrastructure per customer. By 1930, electricity had transformed the lives of many city dwellers but rural populations remained in the dark (21).

As electric power networks grew and interconnected with one another across the globe, both following and driving industrial development, the value and reach of emerging regional and national grids demanded additional attention from national governments. During that period the private energy sector began to shift towards a collection of public and private approaches with primarily state ownership and/or control of national and regional power systems (25). This transition from early private enterprise to a regulated utility monopoly model was “natural” (26) for centralized grids that provided service with high fixed costs for shared infrastructure.
Following the engagement of the public sector and regulators in centralized electricity production, rural electrification efforts were initiated to expand access and reach new generation resources, often hydroelectricity. The arrangement stands in contrast to decentralized energy systems where there is no physically shared and dedicated infrastructure system required.

The Tennessee Valley Authority (TVA) is a classic example of early efforts public institutions took to drive development of electricity networks in areas of deprivation that were neglected by the private sector with joint access and generation projects. It is also unique in its relation to broader development, an effort that was part of the broader “New Deal” program of United States government infrastructure projects and financial reform in the 1930’s. The project became an all-encompassing institution that not only built electric infrastructure but also operated as a utility, river water management agency, and development organization. It featured many elements that are present in current-day debates around rural electrification and the role of linked generation, transmission, and distribution system investment. The TVA was promoted partially as a jobs and economic development program (which has been shown to hold true to its promise on a regional basis in ex post econometric analysis (27)) and also on the basis of providing populist “Electricity for All” (see Figure 2 for evidence of this phrase’s enduring appeal for large energy projects and programs) while taming the capricious Tennessee River to make it navigable and less disruptive with a series of large hydroelectric dams (28). Today the Tennessee River Valley is seamlessly interconnected with the rest of the Eastern Interconnection transmission grid and has experienced a significant regional increase in jobs and ongoing manufacturing capacity (28), but during and after the development of the TVA, the project encountered opposition and criticism from many perspectives (29). The emerging but powerful energy sector whose pricing was undercut by the subsidized tariffs of the TVA denounced the project as wasteful and anti-capitalist (30). Strong objections arose to the allocation of jobs and services in the Valley that magnified existing racial and socioeconomic disparities in the region (31). Furthermore, several rural, poor communities were displaced from their homes in areas that were flooded for hydroelectric storage reservoirs as the project transformed the valley (32).

Broadly stated, similar patterns of on-grid inclusion and off-grid marginalization as seen in the TVA began to play out as power grids became the focus of ‘Development’ plans in non-industrialized nations worldwide (33). The dominant mechanisms of this evolution included: combinations of private and public initiative (sometimes with opaque and/or corrupt governance); largely ignored but important issues of equity in development; and patterns of investment in transmission projects that benefit primarily existing beneficiaries of electricity in urban and industrial centers. The costs of these publicly funded projects are not only financial, but also include a loss of land to eminent domain, environmental degradation, and others that are often borne by rural people who are marginalized and without power. While power reached the cities and industry of the developing world in the early 1900’s around the same time as it reached cities in the current industrialized world (34), rural (and poor urban area) electrification has significantly lagged. The current electrification rate in developing countries, as classified by the International Energy Agency, is 77%, compared to OECD nations with an electrification rate of 99% (35). The electrification rate in Kenya, where my work was focused, is 20% (17,36).
A key challenge in rural electrification efforts is the cost of building the distribution system to go the “last mile” (this is also noted as a key challenge for distributed off-grid power systems). A recent study focused on Kenya found that the marginal capital cost of connecting customers in places with high density and existing power infrastructure is relatively low, $1000 USD, but the cost is $4000 USD or more in less dense rural areas where people also have a lower ability to pay for the service (or buy appliances that result in higher demand) (37). In the context of typical annual household expenditures (approximately $1,000 in Kenya, which is roughly a median case in Sub-Saharan Africa) and the fact that typical household spending on energy is 5-10% of the annual budget (38), it is clear that it is often financially a loss for system operators to expand electricity services to the rural poor, who may not be able to consume energy at a rate that allows steep connection costs to be recouped.

In many areas, even prior to addressing distribution issues, power generation and transmission needs to be close enough to enable a connection. Transmission networks reach out to meet load centers, connect with generation that is in a geographically fixed area (e.g., a renewable resource area), and to interconnect with adjacent power grids. There are many such projects currently under way in the developing world, including contested (and funded by multinational development agencies) generation and transmission expansion in the East African corridor, which includes large projects such as Gibe III and IV hydroelectric projects in Ethiopia, the Eastern Electricity Highway Project connecting Kenya and Ethiopia, the Lake Turkana Wind Farm in Kenya, geothermal resource expansion in Burundi, Grand Inga Dam in DRC, etc. Much of the discussion today focuses on many of the same issues as with the TVA, where promised growth in the industrial economy and marginal (often very small) increases in functional energy access are weighed through political processes against displacement of populations (39), disproportionate impacts on the poor and marginalized people (40), and often in the context of political tension (41).
Figure 2: Graphic artifacts illustrating the “energy for all” rallying cry that has accompanied numerous on- and (now) off-grid power initiatives, including A) the Tennessee Valley Authority (circa 1933, B) A banner for an Easter celebration at the Gibe III dam construction site in Ethiopia (circa 2013), and C) the Sustainable Energy for All Initiative by the United Nations (circa 2014) Images are from: (A) http://newdeal.feri.org/tva/, (B) http://www.gibe3.com.et/News%20letter%20volume%208....pdf, and (C) www.se4all.org

INFORMATION AND MARKET TRANSFORMATION
Against a historical backdrop of gaps in grid service for those on the margins, the growing off-grid electricity sector holds the promise to bridge them, but there are critical issues to address to accelerate growth overall in off-grid power while also protecting buyers and end-users who are newly connected through a decentralized energy system. From a regulatory perspective, unlike grid extension that is often a national or sub-national concern, the off-grid power market is diffuse and global in scope while still ultimately reaching people in particular nations and places. There is no clear need for geographic monopoly among providers, as there is no permanent, dedicated infrastructure network needed for off-grid power. Thus the regulatory and market support challenge is to address local concerns and needs in the context of global markets and production where harmonized approaches can enable economies of scale to mass-produce solar energy systems. In response new programs have emerged to support the global market like the World Bank Group’s Lighting Global c and the German Corporation for International Cooperation’s (GIZ) EnDev.

c I have worked with the Lighting Global program since 2009.
The approach Lighting Global has taken includes running a quality assurance program for off-grid solar, generating and disseminating market research, doing outreach to national and global policymakers to address unintended barriers and mismatch in regulation, cultivating access to finance throughout the supply chain, making business-to-business links between vetted firms, and working to develop consumer awareness and knowledge of off-grid solar technology systems. This diverse set of activities can ultimately be classified as fixing different types of information failures in the market: about product quality, the influence of regulations, the existence of good partners, and other factors. This places the approach in contrast to other forms of “development aid” that is structured around tenders for large orders of goods to be given away or subsidized.

The need for quality assurance, among other support mechanisms for the solar market, is real. We documented in Kenya in 2008-2009 that users of low-quality LED flashlights were 60% less likely to adopt good-quality solar LED lighting (n=23) than similar individuals who had no experience with LEDs (42). This assessment confirmed earlier work that identified market failures in the Kenya solar home system market (43), providing further evidence of the need—generally unfilled—for better quality assurance. Quality is also a key determinant for the environmental and economic performance of decentralized energy systems. A life cycle analysis of pico-solar devices we completed in 2013 demonstrated that energy “debt” incurred during manufacturing and distribution is paid back typically in 20-50 days from expected reductions in fuel-based lighting use (which is similar in many cases to simple economic payback time). The longer a product continues to provide service the better the environmental and economic returns on the investment. Figure 3 shows that with a two-year lifetime, this corresponds to an energy return on investment ratio of 10-20, and much higher returns are possible (along with lower) depending on the quality and performance of systems. (44)

![Figure 3](image)

**Figure 3:** The implications of durability and performance for the energy return on investment (EROI) for off-grid solar lighting. Performance is related to the kerosene offset fraction—the fraction of baseline kerosene use that is eliminated upon adoption of off-grid solar, where higher fractions yield better returns. Better durability can lead to longer product lifetimes over which greater benefits can accrue. (copied from: *High Life Cycle Efficacy Explains Fast Energy Payback for Improved Off-grid Lighting Systems*, Alstone et al. (2014), Journal of Industrial Ecology 18 (5).)
Lighting Global was originally pilot tested in the Kenya market, and through the history of the program there has been an effort to benchmark and track the development of the solar market there on the retail level. A work I co-authored (published in September 2015 through Lighting Global), *The Rise of Solar*, summarizes the outcomes of a retail survey of off-grid lighting sellers in three towns in Kenya: Kericho, Brooke, and Talek. Our 2014 survey (a collaboration between my Berkeley team and Lighting Global) was the third in a longitudinal series that includes data points from 2009 and 2012 (45). It shows how the retail market for preconfigured pico-solar energy systems has rapidly grown, from less than 5% of the sales revenue in 2009 (among all off-grid lighting, including flashlights) to 20% in 2012 and 85% in 2014. Figure 4 shows how good quality solar energy systems have gone from a technology on the margins to the mainstream along with solar energy more broadly. While there continue to be high volumes of LED flashlights (typically low-quality (46)) sold through retail channels, an rapidly increasing share is held by solar, particularly on spending and revenue, and pico-solar is now a relatively ubiquitous product category in market centers across Kenya.

We documented the evolution of the sellers in retail markets over that time as well, who include street hawkers, informal wholesale distributors, formal retail and distribution shops, and agents of vertically integrated off-grid energy companies. Through the course of our study, access to mobile telecommunications services and an increasing fraction of revenue for solar goods as a sales line have been key to their changing business practices and makeup. The sellers made partnerships with a variety of distributors, where decisions about what products should be imported and sold through regional and retail networks are important drivers for the national availability of good quality solar. These national distribution, retail, and service networks are vital physical-social links between people without energy access and global-scale markets for electronic goods. As an ICT layer is added and integrated throughout this decentralized energy services network, public institutions and private organizations are working to build an integrated information-energy system.

The Chapters that follow map and explore evolving structure of the off-grid power sector as ICT and PAYG become key constituents, and were originally published through the Lighting Global institutional platform as part of a series that includes *The Rise of Solar*. Chapter 2, *Off-grid Power and Connectivity*, frames the role of PAYG as a key element for accelerating energy access through off-grid solar. Chapter 3, *Quality Communication*, presents our findings related to the dynamics of the retail market and how information about the quality of technology flows bidirectionally along with goods and capital. Taken together, this pair of works uncovers and describes new concerns and resources for market transformation of decentralized energy systems.
Figure 4: Product availability, monthly sales, and monthly revenue for 2009, 2012, and 2014 for all three towns. Solar products that are quality-verified (satisfy the Lighting Global Minimum Quality Standards) are represented in gold. Solar products that are not quality verified are represented in yellow, and non-solar products that are not quality-verified are represented in grey. (copied from *The Rise of Solar*, Turman-Bryant et al. (2015), Lighting Global Market Research Report, https://www.lightingglobal.org/resources/)
Chapter 2

Off-grid Power and Connectivity

Pay-as-you-go financing and digital supply chains for pico-solar

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Abstract

Pay-as-you-go (PAYG) solar home systems are a fast-growing segment of the off-grid power sector. Our research team studied the PAYG market in Kenya, where there are (circa early 2015) twice as many active deployments of PAYG as any other country in the early market. Working with M-KOPA and SunnyMoney in depth we obtained customer surveys for users of PAYG (n=205), combined with long-term retail market study, focus groups, and structured interviews. In a global survey of firms we document diverse approaches with variations in technology platform for payment and verification, pricing strategy, offer type, system scale, and business partnership strategies. We found strong evidence that PAYG accelerates energy access, with early indications of scale on the order of a factor of two higher adoption rates among people who are offered an opportunity to buy. This acceleration derives from a combination of financing to reduce liquidity barriers for initial purchase and increased trust in the quality of the technology system and likelihood of support from the original seller. Along with supporting rapid deployment of solar home systems, the remote connectivity and business process data that are available (in varying degrees) from PAYG systems hold promise to support new approaches to market research and after-sales service. We also identify a set of critical issues for understanding and supporting the market. One is the role of telecommunications firms that operate important mobile money systems and may also compete in the PAYG market with their own or a partner’s offering. We also identify urban-to-rural subsidy that is implicit in uniform national pricing, a disconnect between financial payback and the human development outcomes from systems that are disabled after partial
payment, and important privacy concerns raised by users with respect to repayment and system operations data use.

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Thank you to the survey and focus group participants, interviewees, and collaborating organizations in off-grid energy and telecommunications. We are particularly grateful for the helpful cooperation to deploy field elements of this work from staff at M-KOPA, SunnyMoney / SolarAid, Angaza, and divi. In addition, we received expert advice and support in the field from our research team, particularly Maina Mumbi and David Mugo. Thanks also for valuable comments, suggestions, and conversations from our colleagues at Lighting Global, UC Berkeley, and participants in seminars and workshops.

Author Contributions: P.A. was lead author and analyst, and overall lead on the research project, D.G. co-authored and contributed to analysis. P.A., D.G., and N.T.B. conducted the field research. A.J. and D.K. were advisors, principal investigators, and contributed to framing and final authoring.
EXECUTIVE SUMMARY
Digitally financed off-grid solar has transitioned from pilot scale to a diverse and substantial sub-sector of the global off-grid energy market. Today nearly 30 companies operating in at least 32 countries provide access to consumer capital for off-grid solar using digital finance, opening access to vital electricity services. Building on the burgeoning pico-power and solar home system (SHS) progress of the last decade, information and communication technology systems are accelerating and reshaping the dynamics of off-grid electricity access by providing financing and increasing connectivity throughout the supply chain. Mirroring trends in mobile money adoption rates, Kenya and other countries in East Africa are early focus areas for deployment, shown in the map below.
There is a wide range of business models that fall under the loose category of digitally-financed or “pay as you go” (PAYG) off-grid energy. Varieties of energy systems with connected hardware and software are currently being explored in a diverse set of regional markets throughout the developing world. The diversity of business models and technologies provides a rich opportunity for learning best practices in customer acquisition, portfolio structure, loan product design, etc. Some of the common models are described as “DESCO” — distributed energy service companies that provide a given level of energy service in exchange for ongoing payments. Others are better described as asset finance or microloan providers, with a transfer of asset ownership to the user after a limited payment period. Others still act as business-to-business (B2B) intermediaries, supplying hardware and software support from global operations to last-mile energy service and payment logistics.

In this report we use a catchall category descriptor of "pay-as-you-go / PAYG" to capture this range of approaches. The dimensions of PAYG for off-grid power include a range of system scales, from ~1 W pico-powered lighting to kilowatt-scale solar home systems and community-scale grids. Connectivity also varies significantly and includes systems with embedded GSM (mobile phone machine-to-machine transfer) modules and mobile-money payments, scratch cards and tactile keypads, or premium SMS. In essence PAYG allows manufacturers and distributors to act on behalf of their customers to access financing through working capital and other funds.

**PAYG in a nutshell:**

PAYG is a microfinance platform for household energy systems that have relatively high up-front capital costs for off-grid consumers.

There is an information technology system that underlies the platform, allowing automated payments and system monitoring / activation. The range of payment and verification systems includes GSM-enabled mobile money payments, scratch cards and tactile keypads, or premium SMS.

In essence PAYG allows manufacturers and distributors to act on behalf of their customers to access financing through working capital and other funds.

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Figure 1: PAYG reach circa 2015: the number of providers identified through a market scoping search, by country. (source: author desk research)
payment systems as well as those with scratch cards and remote keypads for entry.

We completed an in-depth field study of PAYG systems in Kenya during 2014, where there has been significant PAYG market growth over the course of the year. The focus of our data collection was on study lamps and pico-solar home systems that are sold to end-users coupled with a credit mechanism (see additional notes below on datasets). Kenya is a unique case study for an “early adopting” country, with a mature mobile money sector (and a dominant provider—M-Pesa through Safaricom), a competitive and growing off-grid solar market, and the city of Nairobi that has emerged as an important hub for information technology, finance, and development aid organizations for all of East Africa. We support our field insights with extensive desk research that focused on the PAYG landscape, energy access needs, and connectivity data.

**ACCESS TO ENERGY, INFORMATION, AND FINANCE THROUGH PAYG**

PAYG systems catalyze increased energy access through financing and through increased connectivity across the supply chain, from head offices to end users operating remotely monitored systems. While the full measureable benefit of PAYG has not yet been rigorously established, early indications are that PAYG dramatically increases levels of access through consumer markets for off-grid power. In SunnyMoney's pilot trials of PAYG study lamps offered through a school sales campaign, the adoption rate was 20-50% while the normal level without PAYG in the same sales channel is 10-15%. This suggests **roughly a doubling to tripling in sales** for lamps in that category. In the case of systems with greater up-front capital investment, including community mini-grids, PAYG technologies and business models are also catalyzing significant growth. As lessons learned are accrued among enterprises and users, accelerated growth in access to solar through PAYG appears possible through a range of channels. In this section we sketch a summary of the different forms of support that PAYG provides to the off-grid lighting market.

**Financing Energy:** The most obviously valuable feature of PAYG systems is the opportunity to lower transaction and management costs on loan and energy service payments, thus enabling consumer financing for loan sizes that are much smaller than previously...
possible. This access to consumer-level financing had long been recognized as a critically important factor for increasing energy access for cash-poor buyers, and it was noted as an important and valuable opportunity by the people our research team heard from in the field. The providers that were the focus of our field research have developed pricing strategies that closely match the daily kerosene spending of potential customers. This allows for cash-constrained consumers to roughly maintain typical spending on energy while receiving a much higher level of service. Furthermore, PAYG models often implicitly help finance the retail supply chain, since smaller outlays are required by sales agents and retailers for stock than a wholesale purchase and resale model.

**Building Trust:** Our findings also showed that the offer of financing helps overcome another critical hurdle: building trust in the quality, performance, and expected utility of systems. Customers in focus groups told us (translated from the Swahili here and in most quotations from focus groups or survey participants) that because PAYG systems have financing they are expected to be “...better because you can return the light before payment is complete if it is not working...that means [the sellers] have confidence with their product”. For the study lamps sold through Sunny Money, nearly 15% of customers chose to pay the lamp in full after far fewer payments than were available in the loan (<30 days, versus the available 70), strengthening the assertion that some buyers were using PAYG to overcome a trust barrier, more so than a capital constraint.

**New consumer insight:** For many PAYG customers, purchasing the system will be among the first times they have had access to financing that is easily traceable and verifiable. In addition, mobile-enabled PAYG provides a window for providers into user behavior that is otherwise unavailable for shaping and supporting off-grid power systems. PAYG systems open opportunities for using repayment histories to establish credit records, and allow for monitoring of nearly real-time power consumption to better understand access dynamics and changing customer demand.

**Amplifying access through finance for expanded service:** Owners of PAYG solar products can leverage their asset for the acquisition of new products if refinancing, or other follow-up offers for financing, is offered. This can enable the addition of extra system components,
compatible appliances, or other goods and services that were previously unaffordable. Over 80% of the customers we interviewed in phone surveys reported interest in financing an expansion of their system through PAYG, particularly for appliances including additional lights, television, radio, etc. (see Figure 3). Furthermore, many organizations engaged with PAYG cite the potential to develop credit scoring and other repayment data derivatives that could open access to financing beyond energy service and appliances.

**Maintenance and monitoring:** GSM technology allows PAYG providers to more closely monitor and respond to changes in system performance, improving the service reliability and durability of energy access. Deploying machine learning and other techniques to analyze large-scale data can lead to prediction and identification of issues with system maintenance (or customer repayment). Furthermore, PAYG allows many providers to have more direct interactions with customers, providing an ongoing channel for after sales service, payment reminders, and other information via SMS. The strength of connected PAYG (and other connectivity-enabled approaches) for supporting reliable, adaptive solar energy access will become clearer as the first wave of systems entering the market today age and are supported with maintenance, expansion, and replacement.

**Connecting supply chains:** Building off-grid power markets means having robust supply and service chains to support adoption, maintenance, and reinvestment. We find that connectivity across the sector, including PAYG and non-PAYG sales, is now a core requirement for successfully delivering good quality and trusted off-grid power systems to retail markets. This means, as growth continues, there are opportunities for a growing, digitally literate young population to engage in “green jobs” for off-grid power (replacing or adding to the activity for sellers of kerosene, batteries, or recharging service). Sales agents, sub-distributors, technicians, and logistics specialists, along with salaried positions farther up the supply chain are all pieces of the off-grid power labor force.

**Building a stronger PAYG market**

PAYG approaches benefit from ongoing support of the broader off-grid power market, but there are some special concerns for specifically encouraging PAYG market growth.

**Access to capital:** Like the broader off-grid solar market, one of the core barriers to scale for PAYG is access to appropriate working capital financing (with a preference for local currency). Access to working capital allows PAYG providers to stock more product in-country, supply larger inventory to retailers and agents, and extend better loan terms to consumers. All of these factors ultimately contribute to higher levels of access. At this point, investment in the PAYG sector has been insufficient to fulfill capital needs for providers. Although more than $70 Million of equity and debt investment in PAYG firms has been publicly announced (originating from over 60 unique investors), a recent report by the Global Off-Grid Lighting Association (2014) cited a sector-wide need of over $1.5 Billion to support consumer finance over the next 2 years. Bridging this gap will be crucial for growth in PAYG and the broader market.

Data showing the reliability of customer repayment in the early market may prove to be a critical element for attracting critically needed financing for growth in the PAYG market.
Debt repayment streams from large groups of customers can be securitized in portfolios that free working capital. Proof of the reliability for repayment (so far many firms claim >90%) provides a foundation for growth capital.

**Transaction fees for mobile money payments:** Many PAYG approaches rely on mobile money systems for payment processing, while others use alternative approaches like agent networks who can receive cash with mobile phone apps or scratch cards. In both cases, there are transaction costs that add to the cost of financing. For mobile money, the costs result from fees levied on transactions by network operators, and for other approaches there are embedded marginal costs for card printing, agent margins, and other needs. These are not insignificant costs and can add up to 15-20% to the overall outlay required by customers based on the observations we made in the field. Reducing these costs could improve PAYG financing access to reach greater numbers of the poor. While there are logistical barriers to reducing costs associated with physical agent networks, the pricing for mobile money systems also depend on the particular mobile payment business model; many services charge relatively large fractions of the total in lower-value transfers. If these fees were waived or reduced for social goods payments like off-grid power access, it could accelerate and streamline progress along with reducing friction in payments.

**Friction in interfaces (both UI and B2B):** There are interface growing pains on both “sides” of the PAYG business model: both the customer user interface (UI) and business to business (B2B) relationships between PAYG and mobile money providers. Users are offered a wide range of both payment and transaction verification systems, most of which are not in common use and may require new learning of the payment steps and processes for every new provider that offers service at costs on the order of several $100’s of thousands USD for software and hardware integration to support deployment (based on anecdotal evidence from a range of implementing and supporting organizations in the PAYG market). PAYG firms also need to manage relationships and software systems with telecommunications firms and equipment providers, often co-locating server hardware and needing careful software development to build a system that can scale and handle enterprise-level payments. In both areas, UI and B2B, there are significant opportunities to reduce barriers to competition between devices and entry to new markets through standardization of the user interfaces and application programming interfaces.

**Reduce exposure to pricing and currency risk:** Any consumer finance platform incurs risk when accessing capital from abroad. Fluctuations in currency can drastically alter the ability of a PAYG provider to service international debt. This risk is less prominent for suppliers of pico products, but should be recognized by providers of larger systems with longer loan tenors.

Changes in technology pricing can also introduce a new risk for PAYG providers and consumers. If a product is sold with a multi-year loan term and the underlying technology drastically drops in price over the repayment period, consumers may feel inadequately served by the provider. This could result in default or consumer dissatisfaction.
Respect Data Privacy Concerns: Customer data access and privacy concerns are important factors in the early market. Many PAYG firms are collecting data on system use but there are scant examples of how these data are put to use for business decisions and processes beyond tracking repayment histories and improving customer service. In focus groups, there was a universal concern over private consumer data being shared externally by the provider, while recognizing the potential for positive returns to consumers from prudent and confidential uses.

NOTES ON THIS STUDY
This study builds on other reports on PAYG that explored key opportunities for accelerating the market. A report from GSMA in 2013 pointed to the need for low-cost machine-to-machine GSM chipsets among other recommendations, and in 2014, a report issued by CGAP mapped the emerging PAYG market and discussed potential opportunities to improve scale. Our work is based on field data in combination with desk research to provide new depth of insight into particular models and markets. This report is rooted in the analysis of the Kenya market, where our work was focused.

Kenya as a pilot: Kenya is a special case for PAYG due to numerous favorable conditions, including an established mobile money sector, popular awareness of solar power, and supportive business and regulatory environments. Many of these same conditions however, are emerging in other markets. There are currently 255 live deployments of mobile money systems in 89 countries and growing. The off-grid solar sector has also experienced recent and rapid growth in other areas of sub-Saharan Africa and Asia, particularly India, Bangladesh, Nepal, Uganda, Tanzania, and many Southeast Asian island countries. Finally, many governments are showing increasing support for renewable energy in the form of VAT reductions, subsidies, and other measures.

Datasets: We draw on several new datasets that were gathered to support this study and other reports during 2014. We primarily highlight insights based on data and observations we obtained through research partnerships with two commercial organizations delivering PAYG-enabled off-grid power in Kenya: SunnyMoney and M-KOPA. M-KOPA is the largest early PAYG solar operator in the world, and during our field research partnership in June 2014, the organization passed 100,000 units sold, nearly all in the previous year. At the time, M-KOPA offered a 5-watt pico solar home system for sale through a retail agent network in Kenya, with payments through the M-Pesa mobile money system. SunnyMoney was pilot testing two technology platforms for PAYG study lamps during the period: divi and Angaza. Divi and Angaza are two start-up companies focused on building general PAYG technology.
platforms (hardware and software combined with payment integration). In the pilot they supported PAYG integration in study lamps (like the Greenlight Planet Sun King Eco, in which the Angaza system was integrated for the pilot). The study lamps were sold in a set of pilots directed by SunnyMoney through a modified version of their institutional school sales program, which, along SunnyMoney’s growing retail network, has lead to purchases of over 1.6 million pico-powered lighting systems. Working with implementation and internal research teams at those organizations, we conducted customer telephone surveys and, in the case of SunnyMoney, a set of focus groups. We also worked to better understand the business models and supply chains for PAYG for those and other organizations active in the space. Data was collected from public sources, such as CrunchBase (for investment data), company press releases, external case studies, news reports, and public interviews. A detailed listing of data generated for this study is in the Annex, and there are more details on the SunnyMoney and M-KOPA PAYG enterprises in the main report.

Keep in mind… It is important to note that the PAYG market is incredibly dynamic. New business models appear almost daily, companies pivot and change approaches, funding is raised, and players disappear. This report presents a snapshot of what our team observed during the June and July of 2014. Since then, even our partners have altered their approaches, with the most notable change coming from M-KOPA, which shifted to a more vertically integrated model that now includes proprietary manufacturing of the system itself. Any conclusions presented in this report are a product of data available during the study period, and do not reflect many of the changes that have occurred in the market since. We have, however, attempted to update general investment and deployment numbers to be current as of February 2015.

Fig. 5. Focus groups for off-grid solar in 2012
(not part of this study, from previous work with Lighting Africa)
TRENDS SUPPORTING PAYG SOLAR

The off-grid solar market has gone from pilot scale to meeting the needs of millions of people over the last 10 years by leveraging trends in the cost and performance of solar photovoltaics (PV), batteries, and efficient loads to move from a nascent technology concept to a growing industry with multiple large players. One measure of this growth is the number of products sold—over 6 million pico-solar products have been sold through channels supported by the Lighting Global program alone. Other off-grid solar channels have also shown strong growth over the same period, notably the IDCOL Solar Home System support program in Bangladesh (over 4 million sold). Solar has been cost competitive for years with kerosene and fee-based mobile phone charging, and the opportunity to eliminate these expensive and, in the case of fuel-based lighting, harmful energy service methods is clear. High quality ready-made solar energy kits are now available at scale on the global market, and a range of business models to deliver and support their adoption are emerging, including PAYG.

The growing standardization of SHS products lends itself well to PAYG business models that limit customizability and repayment schedules. “Traditional” approaches to SHS deployment, where each system is bespoke and has a unique price, offer challenges to financing since each system would thus have unique repayment terms and transaction costs. With modular and standardized technologies, a broadly applicable (countrywide) payment term can be offered, which becomes much easier to administer and market.

Over the same period that pico-solar has become a more prominent tool in supplying energy access to the poor, peoples’ access to mobile phones has dramatically increased in the developing world. There are currently 90 active mobile phone subscriptions for every 100 people in the developing world (70/100 in Kenya), and a growing share of the population is using smart phones (currently about 10% with projections for fast growth as the price of handsets fall). This new wave of connectivity has led to a range of changes across developing world economies, notably the rise of mobile money systems that are core to several PAYG strategies. Kenya is an early leader in mobile money utilization, with the majority of the population (roughly 70% as of 2013) reporting using mobile payments on a regular basis. In other developing world nations, rates of use are lower but growing fast.
PAYG companies have taken advantage of the growth in mobile money markets, establishing operations in many of the early adopter regions: Kenya, Tanzania, Uganda, India, and others. The early growth in the Kenya PAYG market (see figure 1)—over double the size of the next market—can be attributed to both the early availability and rapid national adoption of mobile money. Kenya is a lead country in mobile money uptake due to a range of factors, including a strong telecom with a large market share (Safaricom), a relatively loose regulatory framework during the early growth of the service, and broad support and investment in marketing and developing a network for the service.9–11

**PAYG AND CONNECTIVITY TAXONOMY**

Pay-as-you-go solar has become a catch-all term to describe off-grid PV energy systems coupled with connectivity or IT-enabled payment systems, allowing a range of business models built on asset finance or fee-for-service models. At this time, we have identified 28 companies currently operating in 32 developing economies that fit our definition of PAYG. According to publicly available information, collectively the firms have deployed over 250,000 systems (across different service levels) and have raised over 80 Million dollars in investment capital (philanthropic, debt, equity, hybrid) from 72 unique organizations and firms. In this section we provide a brief outline of the broad PAYG landscape.

The core of PAYG is that it is a **financing platform** that builds on the unique opportunities in each market. Some of the key factors present in most current business models are: the active use of mobile telecommunications systems, widespread agent networks, distribution partners, and a longer term firm-consumer relationship than standard retail. While PAYG is primarily a means of providing financing options to consumers, it also enables a greater degree of after sales service and remote system monitoring and data collection, which allows the business to have a longer-term direct relationship with the consumer and the opportunity to offer referrals and other benefits.

Traditional finance institutions have tended to avoid consumer credit in the off-grid energy space for a number of reasons. First, the transaction costs associated with managing such small loans (anywhere from $10 for pico-products to more than $250 for larger home systems) can be disproportionately high in comparison to the returns. The risk profile for such products is still largely unknown, and until recently, the technology risk was perceived as too high to extend long-term loans. Finally, lending for off-grid energy products is outside of the core business of traditional financial institutions, which means that there is often an overall lack of internal technical capacity to (a) assess product quality, (b) select products among a wide range of competitors, or (c) effectively market or distribute products. While there are examples of microfinance providing successful programs in support of off-grid
energy (Grameen Shakti in India, Prodem in Bolivia, IDCOL in Bangladesh), few have been able to scale to the degree that PAYG companies have been able to without subsidy.

**DIMENSIONS OF PAYG**
The PAYG landscape can be delineated for comparison using a number of product and business model attributes. We will attempt to classify the distinguishing characteristics here, although the landscape is ever evolving and will include other novel approaches in the near future. This section will make the following distinctions:

1. **System Size**
2. **Customer Relationship**
3. **Payment Platform**
4. **Connectivity**
5. **Partnership Strategy**

**System Size**
PAYG solar products can be divided by the system size, which dictates the service level that each provides. While there is no agreed on and fixed taxonomy of systems, many are categorized as pico solar, ranging typically from 0.5W to 10W, and include study lamps, lanterns, and basic solar-home systems like the M-KOPA III. Others may provide standalone systems that are either self- or professionally-installed (such as the one provided by SunTransfer or SolarNow), and include the ability to power small appliances such as fans, DC televisions, and even small refrigerators with a solar module power rating of roughly 10 to 200 Watts. **Community level, shared mini-grid systems** are an equally broad category, and range from the kilowatt scale (such as Mera Gao’s DC mini-grid), which provide basic services, to larger multi-kW systems (such as those being developed by Power Hive), which often power AC appliances and supply productive power. The distinguishing characteristic of mini-grid systems is the interconnection between homes (and businesses), which can allow for a more efficient use of generated power and enables economies of scale from diversity in loads and declining unit costs in some basic technology systems.

At this time, pico and household products are seeing the largest growth in the PAYG space, with over 200,000 systems deployed to-date. However, the market potential for the off-grid energy sector overall is largely untapped, with over 500 million households globally lacking reliable power.\(^7\)\(^12\).

**Customer Relationship**
The broad categories of consumer relationships available are micro-loan, energy service, and business-to-business (B2B) hardware/software.

Within each category there are also different approaches, which are outlined below:

**Micro-loan:** Firms such as M-KOPA, Nova Lumos, Azuri, and Simpa Networks fall under the umbrella of asset finance, or micro-loan. While the specific criteria differ between firms, typically the same three-step process is followed for end customers:
1. Down payment and relatively informal credit check
2. Payment series via proprietary or licensed platform
3. Device is unlocked and owned by the customer

*Energy Service*: Another approach is the distributed energy service company model, employed by firms like Off-Grid Electric, where rather than financing an asset, the company provides an electricity service much like a modern utility does. That service comes from a company-owned solar system which is roof mounted. The user provides an installation or down payment, slightly de-risking the investment for the firm; however at no point does the consumer own the asset outright (even after the full cost has been repaid).

*B2B hardware/software*: There are significant needs in the PAYG market for specialized IT hardware and software. Some firms focus on B2B offerings that provide critical support for providers to better serve their customers, as exemplified by the approach of two of the firms we worked with in detail, Angaza Design and Divi Power. Both provide specialized software and hardware, producing and supporting technology systems that can be integrated with an off-grid solar product to allow for remote activation and deactivation, payment stream management, and usage tracking. In general these approaches are neutral to the consumer relationship and could support either a micro-loan or service model. Many firms that developed in-house hardware and software platforms for deployment in markets also now offer their platforms as licensed technology.

Fig. 8. A rough categorization of PAYG enterprise circa early 2015 along the dimension of customer relationship.
PAYG providers employ a number of approaches to enable payments for their product or service. Some, like M-KOPA, rely on an established mobile money network. In their case, a partnership with M-Pesa in Kenya allows for nearly seamless product activation with no agent interaction after the initial purchase. Others, such as Simpa Networks and Azuri Technologies, have developed a scratch card model with distributing agents across the countries where they operate that doesn't depend on mobile connectivity but does require management of the agent network. Nova Lumos employs mobile airtime as a virtual currency, allowing users to pay for service using mobile phone credit. Other models require specialized agents to accept cash payments, and then activate solar lights through either (a) a cable, (b) bluetooth, (c) or a manually-entered SMS code. Overall, 60% of the firms we identified use mobile payments and 40% use an alternative.

Product repayment periods vary widely amongst systems and depend on (a) the total cost of the product, (b) the risk mitigation strategy of the firm (the longer the tenor, the higher the risk), (c) the cost of capital to the PAYG firm, and (d) the regulatory framework in the market, such as VAT and other regulations that influence system price. For the products that we studied in Kenya, payment tenors ranged from just over 10 weeks to just under 1 year for average repayment. Some current PAYG systems in Kenya have terms that extend up to 3 years.

**Partnership Strategy**

Firms in the PAYG space have diverse levels of integration across the supply chain and approaches to marketing and distribution. Partnerships are being made on hardware, distribution, payment, or other core aspects of the business. For example, some firms (such as Azuri) have an essentially vertically integrated supply chain from manufacturing / design to last-mile distribution and payment. Others, such as Fenix International and Nova Lumos, have partnerships with local telecommunications companies to support sales and
delivery to the consumer. Still others, like M-KOPA (circa June 2014), have a device that is branded with a telecommunications company logo and partner manufacturing logo, but conduct the majority of marketing and distribution themselves. Some “business to business” oriented firms (e.g., Angaza and divi) are focused on situating themselves as a coordinator between manufacturing, distribution, and telecommunications integration.

### Connectivity

PAYG technologies can also be distinguished by the level of connectivity used for payment, verification, and customer relationship management. The choice depends on the availability and adoption rates for mobile payment and data transfer service, reach into rural areas without continuous connectivity, and other priorities. The spectrum runs from systems that are fully online, including mobile money and remote, real-time connections with the energy system to those that are only tenuously or intermittently connected. The different arrangements have implications for the way business models can be structured, the cost of implementing the system (additional hardware or integration costs), the implied requirements for connectivity and access to mobile phone networks for operating the system, the frequency and scale of system monitoring data available, and the user and retailer experiences.
“Full connectivity” systems like the M-KOPA III often include a GSM component embedded in the hardware for the solar energy system, allowing bidirectional communication with central servers in near real-time (“machine to machine” or M2M data). These systems not only support remote lock and unlock capability, but also operations and performance data transfer. In systems with full connectivity, payments are often made via mobile money, and central staff can reach customers for service and repayment inquiries. The retail staff may also have augmented access to information and financing for stock through digital connectivity to the PAYG provider.

Fig. 10. Flow of goods, information, and money for “full connectivity” PAYG
The two study lamp pico-solar products that were part of our study--those developed by Angaza and Divi Power--utilized a periodic connection with smart phones to verify payment and unlock the solar device. In this case, unlocking was accomplished by connecting the device to a dealer’s smartphone, where a proprietary application accounted for customer credit, supplied an unlock code to the solar device, and facilitated a temporary bidirectional data transfer. All performance data is stored on the device until an internet connection is established, at which point it is downloaded from the device and sent to the central office via cellular network. The payments in this case can alternatively be made through mobile money or through a cash payment to the dealer, as is shown in the figure below.

Fig. 11. Flow of goods, information, and money for “smart phone unlock” PAYG

*notes: requires smart phone for connection; monitoring data only available intermittently
Other PAYG systems such as the Simpa Networks Progressive Purchase device or Azuri Indigo Duo are activated by keypad--using a scratchcard or SMS-generated codes--and no direct connection is ever made between the solar devices and a central server. Such systems only have lock and unlock capability and no data transfer. To prevent codes from being used multiple times, the typical sequence of operations begins with the purchase of a scratch card, then the code from that card is sent via text message by the customer to an automated system along with their account number (or it is linked with their mobile phone number). That system verifies the scratch card number, matches the payment to a customer account, and sends back a unique unlock code for entry on a keypad connected to the solar device. An onboard microprocessor in the solar device recognizes valid unlock codes and independently tracks progress towards full repayment. An alternative to this model is directly selling keypad-ready codes at the retail level, where retailers use their smartphones (or standard phone) to generate a code for customers who pay for them in cash.

Fig. 12. Flow of goods, information, and money for "scratch card / retail code" PAYG
STUDY METHODS AND CONTEXT

Our mixed-methods study of the off-grid lighting market combines end-user research (surveys and focus groups), in-country supply chain observation (surveys at retail shops, with distributors, and supporting organizations), and analytics of global dynamics (spread of mobile money, trends in underlying technology and policy context). The focus of the end-user and supply chain research is Kenya, concentrating in particular on towns where our partner organizations have been active. This strategy was adopted to capture an in-depth view of the dynamics for the emerging PAYG marketplace to bolster broader analytics of current market trends or issues. Our effort builds on past work by the Lighting Africa program, other institutions, and a growing set of researchers focused on understanding and shaping the off-grid power market.

Kenya is a special case for solar and off-grid power in general, and particularly for PAYG, where the early success of M-KOPA was burgeoned by a growing pico-solar market and by Safaricom’s dominant and near-ubiquitous M-Pesa mobile money platform. Most other markets have earlier-stage pico-solar and mobile money marketplaces, making Kenya either a special case, an indication of things to come, a learning experience, or some combination of those.

Our work:

This report is based on years of experience in the broader off-grid power market and focuses the analysis on insights gathered in 2014, during 2 months of field research in Kenya and approximately 4 months of data gathering that followed.

Our work in Kenya included surveys of 132 local retailers and wholesale traders, 15 national distributors, and 6 finance professionals. We worked closely with in-country partners SunnyMoney, M-KOPA, Angaza Design, and Divi Power to conduct 215 customer phone surveys, as well as 4 customer focus groups in 2 locations. In addition, our team collected publicly available information on 30 PAYG providers operating in 32 countries, which included system size, total number of customers, total investment per company, etc.
Research partner organizations:

In this section we summarize general information on the research partners in our study. With each partner we worked to understand their business model in depth and also executed a telephone survey of customers. In addition to these deep dives, brand-agnostic research in the Kenya retail market for off-grid solar significantly augmented these case studies in developing our findings. The methods included structured interviews with a range of stakeholders and experts in the supply chain for off-grid energy and PAYG firms along with retail-level surveys of the Kenya market.

M-KOPA is the largest PAYG firm in the early market, passing 100,000 systems in June 2014 during our field study and having reached over 150,000 and expanded beyond Kenya by 2015. In June 2014, M-KOPA sold a d.light-manufactured solar home system (5 W solar) that included 3 lights and a radio, the D-20g. The offer is detailed in the Table below along with others. Prior to our study M-KOPA sold the D10, a slightly lower-service system, also made by d.light, for a lower price point, 40 Ksh per day. At the conclusion of our study period, M-KOPA launched a new version of their product, the M-KOPA III (8 W solar), produced and sold solely under an M-KOPA brand (i.e., no longer co-branded with d.light). The price on the new system has also been reduced, to 40 Ksh per day.

![M-KOPA Customer Care operations center, and the M-KOPA branded d.light d20g circa June 2014, in Nairobi.](image-url)
SunnyMoney and SolarAid are the commercial and charitable arms of an organization that has sold over 1.5 million solar lights (as of early 2015), the vast majority of which are not PAYG. Selling through institutional partnerships with schools and a retail agent network, the approach has driven fast growth in the early-pico solar market. SunnyMoney (SM) was working with two integrators of PAYG study lamps during our research period, both of which supported independent PAYG pilots through the SunnyMoney schools campaign in Kenya. The first, Angaza, is partnered with Greenlight Planet (GLP) to offer PAYG-enabled “Easy Buy” SunKing Eco lamps. SunnyMoney specified a pay-off period of approximately 10 weeks using M-Pesa for the Angaza lamps. The pilot was the first deployment for the Eco Easy Buy. The second partner, divi Power, offered a PAYG study lamp known as the divilite (similar in performance and features to the Eco). Its pay-off period was 5 weeks, with cash payments (in the pilot tests we observed). As a benchmark, the standard Eco has a normal cost through the SunnyMoney Kenya supply chain of 1000 Ksh (~12 USD).
Table 1: Summary information on PAYG systems that were the subject of our research focus.

<table>
<thead>
<tr>
<th>System:</th>
<th>M-KOPA / d.light D10</th>
<th>M-KOPA / d.light D20g</th>
<th>SM / Angaza / GLP Sun King Eco</th>
<th>SM / divi / Divilite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Form Factor</td>
<td>Pico-SHS</td>
<td>Pico-SHS</td>
<td>Study lamp</td>
<td>Study lamp</td>
</tr>
<tr>
<td>Branding</td>
<td>M-KOPA / Safaricom</td>
<td>M-KOPA / Safaricom</td>
<td>SunnyMoney / Angaza / Greenlight Planet</td>
<td>SunnyMoney/ divi</td>
</tr>
<tr>
<td>PV Power Rating</td>
<td>4 W</td>
<td>5 W</td>
<td>0.5 W</td>
<td>0.5 W</td>
</tr>
<tr>
<td>Accessories</td>
<td>USB phone charging</td>
<td>USB phone charging, includes a radio</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Down payment</td>
<td>2500 Ksh (USD ~29)</td>
<td>2999 Ksh (USD ~35)</td>
<td>200 Ksh (USD ~2.30)</td>
<td>200 Ksh (USD ~2.30)</td>
</tr>
<tr>
<td>Recurring payment</td>
<td>40 Ksh</td>
<td>50</td>
<td>110 Ksh</td>
<td>200 Ksh (USD ~2.30)</td>
</tr>
<tr>
<td>recession</td>
<td>daily</td>
<td>daily</td>
<td>weekly</td>
<td>weekly</td>
</tr>
<tr>
<td>Number of periods</td>
<td>365</td>
<td>360</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>Total outlay</td>
<td>17,100 Ksh + 100’s-2000 fees** (USD ~200 + 20)</td>
<td>21,000 ksh + 100’s-2000 fees** (USD ~240 + 20)</td>
<td>1300 Ksh + up to 220 fees** (USD ~15 + 2.60)</td>
<td>1200 Ksh (USD ~14)</td>
</tr>
<tr>
<td>Payment Mechanism</td>
<td>M-Pesa Paybill</td>
<td>M-Pesa Paybill</td>
<td>M-Pesa Paybill (collected by the Agent / HeadTacher)</td>
<td>Cash Payment</td>
</tr>
<tr>
<td>“Unlock” mechanism</td>
<td>GSM / M2M</td>
<td>GSM / M2M</td>
<td>Smartphone App + cable connection</td>
<td>Smartphone App + Bluetooth connection</td>
</tr>
<tr>
<td>Lighting Global QA Verified?</td>
<td>No*</td>
<td>Yes</td>
<td>Yes, for the “standard” Eco</td>
<td>No*</td>
</tr>
</tbody>
</table>

* While these are not verified by Lighting Global there were no obvious quality issues with these lamps that we were able to observe in the field or other informal settings. Note that this is not meant as an endorsement or declaration of nonconformance with respect to the quality of the product on behalf of Lighting Global. It is an observation by the field research team based on limited field-based observation, in support of this analysis.

** The sum total fees for cash transfer depends on the frequency and size of consumer payments. More frequent, smaller payments incur higher fees as a fraction of the total and larger transfers typically achieve lower transfer fees. The totals shown here do not include any discounting for the reduced future value of money.
OVERCOMING ENERGY ACCESS BARRIERS WITH PAYG

Pay-as-you-go provides a technological platform that addresses many of the factors that impede the widespread adoption of off-grid solar. Not only does PAYG supply necessary financing for poor consumers, but also allows last-mile distributors to stock more inventory, signals quality to the end consumer, reduces the cost of monitoring and after-sales service, and improves visibility in the market so businesses and supporting institutions can adapt to consumer needs more dynamically. Concurrently, new barriers related to implementing more complex, linked technology and human resource systems arise that should be addressed by manufacturers, distributors, and supporting organizations to ensure the greatest impact and reach.

UP-FRONT COST

The typical purchase price of a solar product can range from nearly $10 for low-end pico products to $200-300 for mid-range low-power solar home systems. In either case, such amounts are prohibitively expensive for some or many of the off-grid poor who may only have cash income of $1-$2 per day. PAYG addresses this barrier by amortizing the high upfront capital cost of products over a time period that the off-grid poor can much more easily accommodate. By reducing the size of cash outlays required, the payment stream for PAYG systems more closely aligns with status quo spending patterns for the incumbent energy services (kerosene and fee-based mobile phone charging). Figure 1 illustrates how the effective daily costs during repayment are similar to typical costs for kerosene for households in Kenya, with vertical lines indicating the daily cost for the SunnyMoney (19Ksh/day – roughly $0.25) and M-KOPA (50 Ksh/day – roughly $0.60) systems that were sold during our 2014 field study. It is notable that given the price of similar alternatives on the retail market suggests annual interest rates of 100-200+% in many of the PAYG models we observed broadly. These financing terms were acceptable to the customers, demonstrating the value of the systems and reflecting the high discount rate of money that is one interpretation of spending behavior by the poor.

While the daily costs for repayment are slightly higher than the average spending on kerosene, it is important to note that the service levels are orders of magnitude better, providing valued service beyond the kerosene that is replaced. The repayment period is not in perpetuity for these two examples, which are both micro-loan models.
Fig. 17. Comparing the status quo daily spending on kerosene, batteries, and mobile phone charging to the effective daily charges for the two PAYG systems we studied in depth (~19 Ksh/day for 10 weeks for the SunnyMoney study lamps and 50 Ksh/day for one year for the M-KOPA pico solar home system). In panel [A], the distribution kerosene spending for lighting is shown. The M-KOPA solar home system provides substantially more lighting service than kerosene lighting and also valued radio and phone charging, so the comparison on cost of kerosene is incomplete. For a better comparison we include spending beyond kerosene in the other panels, including [B] dry cell batteries (normally purchased to power radios) and [C] with mobile phone charging fees. The spending data displayed in grey in the first panel are from the Kenya Integrated Household Budget Survey for a benchmark reference (2005, n = 9,432 responses) and have been adjusted to 2014 values using the Kenya Consumer Price Index. The spending data displayed in blue in all panels are self-reported estimates from the survey our team deployed to individuals who purchased a PAYG solar system (2014, n=205). The values are what they recall spending per day on kerosene, dry cell batteries, and mobile phone charging before purchasing the system.
Building trust in clean energy technologies remains a great concern in these emerging markets, and PAYG can instill trust along two distinct dimensions: trust in the quality of the products and trust in the match between a product's performance and household needs. Customers in the focus groups made a clear link between PAYG finance and trust in quality, pointing out that by shifting more early failure or underperformance risk to the manufacturer, there are added incentives to ensure quality and meeting customer expectations. One of the focus group participants said, “If you see someone giving you a lamp to pay slowly, that means they have confidence with their product.”

Strengthened trust in performance value derives from PAYG allowing a consumer to test the product for some time without paying the full cost, giving the consumer the opportunity to stop payments if product performance is not as advertised. Some customers have the ability to pay full cost and use the opportunity to try products at home for a relatively low outlay, paying in full following a short initial period of use.

We can observe how for some customers, overcoming this initial performance trust barrier behavior leads to fast repayment (if they did not also need financing to overcome cost

![Fig. 18. Diverse paths to repayment (or not) for lamps in a SunnyMoney pilot. These plots trace the repayment behavior of a sample of anonymous individuals in SunnyMoney pilot tests, who pay over the course of 10 weeks. The range of paths in repayment indicate diversity in behavior for those that both did and did not eventually pay off the lamps (indicated with split plots and colors). The dotted line indicates 100% repayment for the study lamp, and the solid lines represent the “ideal” repayment behavior, i.e., the trend that occurs if an individual makes each payment exactly on the timeline suggested in the advertising and marketing literature. Eventually 80% of customers in the trial completed the payments (the “TRUE” categorization in the legend).]
The pattern emerges from payment data we analyzed from Sunny Money customers (see figures below). Out of the ~80% of customers in the trials that eventually completed the repayment cycle, there is a clear subset of customers (about 15% of those who paid fully), who made a full repayment in the initial 30 days following deposit. While it is possible that some of these customers were able to pay off their products early with windfalls of cash (e.g., from either their employer, remittances, or another source), we have reason to believe based on qualitative data from focus groups and surveys that this repayment behavior illustrates that for some customers.

![Figure 19. For those who eventually pay off a study lamp (from the previous figure), the number of days until the lamp is fully paid. A vertical line indicates the expected repayment date based on product literature (10 weeks after purchase).](image)

**Retailer Resource Constraints**

Retailers and potential sales agents in Kenya may be as resource constrained as consumers, which limits their ability to purchase sufficient inventory. During our retail surveys, many of the interviewees commented on their inability to fulfill customer demand, often due to their own resource constraints and the requirements of manufacturers to have products paid-in-full upon delivery. PAYG providers typically require retailers to only pay a deposit amount up-front (i.e. the PAYG company retains the majority of default risk), which is a fraction of the total unit price and lower than typical wholesale prices. When incorporated into the retail market, PAYG financing thus allows retailers to carry a larger inventory of the PAYG product with reduced needs for retail-level working capital (the working capital debt is essentially taken on by the PAYG organization). Our team heard from retailers about the dynamic of getting extended credit for stocks after repeated good business with their supplier. In an off-grid and remote town in southwestern Kenya, an M-KOPA saleswoman was so successful in her first three months of sales that she was given the opportunity to double the number of systems stocked in her store. Depending on the structure of retail incentives and business relationships, PAYG can essentially offer credit to both end-users and the retail network by restructuring payments for both.

**After Sales Service**

Product after-sales service has often been a significant barrier for solar providers in developing countries and is in many ways related to the aforementioned concerns about quality. The retail surveys our team conducted confirmed this as a continued source of concern. In the case of permanently and intermittently connected PAYG, overcoming this barrier can be supported through real time feedback to manufacturers regarding product
performance and use (typically in the form of voltage, current, runtime, charging, etc. data). Since there is risk split between buyers and sellers, there are stronger-than-normal incentives for firms to more rapidly honor warranties and conduct maintenance that reduce payment stream interruption. Firms with capabilities for monitoring (either the payment stream or remote monitoring of system performance) can act proactively, contacting users when products begin to malfunction in order to prevent system failures. In turn, an improved after-sales service model may attract skeptical consumers who previously perceived the risk of investing in unknown or poorly understood technology as too high.

**Market Intelligence**

By collecting significant data around consumer behavior, PAYG firms also have strong advantages over traditional players in understanding the performance of their product and shifts in consumer behavior. In particular, home system PAYG firms can more rapidly respond to changing consumer consumption patterns and provide users with upgraded products (e.g., larger batteries or new converters and connectors), new appliances and loads, or entirely new and expanded systems. As the market shifts, PAYG providers are better able to respond by releasing new products and services. Furthermore, system monitoring and customer data allow companies to gather real-time feedback related to product performance in the field to inform product improvement for the next iteration. The direct connectivity enabled by some of the PAYG systems also facilitates more fluid communication with customers. In short, the information that can be collected related to device performance, consumer preferences, and payment history could form the core of streamlined models for market monitoring, regulation, and support with appropriate levels of transparency and access to data.

These customer data may be particularly useful for supporting expansion in system capabilities. The figure below shows the category of improvement that is mentioned by customers we surveyed. For users of study lamps without mobile phone charging (SunnyMoney) the key priority is obtaining that recharging feature. Other high priority services are brighter lights, radio, and television. The majority of customers spoke about system expansion in terms of service, rather than technical expansion along engineering terms (e.g., the size of solar module, battery, and other components). While an expansion in service may entail expanding both the energy side of the system and adding appliances, it is the service that is a key priority. Thus combined packages of expanded system capabilities should include both to improve their appeal. These offers could be targeted based on repayment and the use of the current system, identifying customers with spare capacity for additional appliances, and/or the ability to pay for an expansion. Targeted and customer-specific data that would have once been difficult or impossible to track and use for supporting expanded access are now built-in to many PAYG business models. We expect a range of approaches to managing these new organizational capabilities for improving service offerings and expanding the reach of off-grid solar.
NEW INTERFACES AND CHALLENGES
While PAYG is an effective approach for reducing many typical barriers to supplying solar products for energy access off the grid, new barriers and frictions not present in a cash-sales market are created through the integration of PAYG technology. In this section we identify some of these emergent issues at the interface between customers and businesses and opportunities to address them.

PAYMENT AND VERIFICATION
In the early PAYG market there are a variety of approaches to payment collection and verification (i.e. controlling whether devices in the field are unlocked or are deactivated due to lack of payment). Every firm we have observed has a slightly different combination of technologies, which could lead to a degree of customer lock-in by introducing a cost to switching platforms based on the time needed to familiarize and learn a new system. For example, M-KOPA accepts mobile money payments using the SafariCom “Paybill” system for a central account, and the system automatically verifies payment using a GSM chip embedded in the product. The SunnyMoney pilot we observed tested two approaches with unique payment methods, both requiring the lamp to be transported to a central location to verify the payment. The Angaza/Greenlight Planet system used the same M-Pesa utility account payment system—Paybill—as M-KOPA and used a cable-based connection with an agent’s smart phone to verify. The divi pilot test combined cash payments to the agent and a Bluetooth connection to their smart phone for verification. Another model in Kenya (exemplified by Azuri) employs scratch cards or remotely-generated unique codes and an agent network as a way of distributing them, with a two-step verification process that does not require connectivity at the premises where the device is located. Other approaches can involve a range of payment platforms and verification steps. These clusters of collection and verification systems used in Kenya and globally are indicative of a market undergoing significant growth, where creativity in new approaches is accommodated with fresh markets and unininitiated users. This is enabling a robust environment for learning what mix of approaches can best meet the needs of sellers and buyers using PAYG systems.
Overall the PAYG customers we surveyed were happy with the payment and verification systems (nearly 90% reported that the process was “easy”, while others indicated that it was okay or that the payment process was hard to understand).

**Transaction Costs**

While PAYG reduces the upfront cost for consumers through the extension of a micro-loan or a fee-for-service model, the currency used for repayment often comes with a fee structure that can significantly impact overall cost to the consumer. Depending on the system size and payment type (for example, in Kenya, M-PESA has 3 types of payments, each with different tariff structures), mobile money fees can reach upwards of 25% of the total system cost to the consumer over the course of repayment, often equal or greater to the financing fees (i.e. the difference in simple cost between a PAYG product and a cash-sales equivalent system).

The payments made by PAYG customers have other transaction costs as well, including the costs associated with conducting diligence on small loans, often through phone or in-person surveys; the cost of the software and hardware required to allow for PAYG, and in cases where agent networks are active participants in fee-payment or verification there are additional costs incurred.

**Feature Requests**

While overall the users of PAYG systems did not express significant concerns over the usability of PAYG devices, the following requests for features represent opportunities for growth in the PAYG sector. These come primarily from the in-depth focus groups we conducted, along with other surveys and conversations.

1. **Expanded ability to activate non-GSM lamps** through a range of channels, not solely through direct agent contact. While the majority of customers reported no issues with the process, some reported difficulties in accomplishing the activation logistics for lamps where a specified dealer agent must activate the lamp. This was in part due to the occasionally complex logistics of locating the agent, traveling long distances (several km in some cases), or the frequency with which users had to take the trip. This was particularly challenging when the agent was not centrally located. As the market grows and a larger agent network is established, the challenges of logistics could be reduced. Non-GSM PAYG lamps are important because currently GSM chips are cost-prohibitive in some applications (like entry-level study lamps) and network coverage is not universal in many rural areas.

2. **New features and options for interfacing with their micro-loan payments:** A set of extensions on the capabilities of payment systems were suggested by the users:
a. **Notification services** (e.g. payment being due): several people in focus groups expressed a desire for an improved notification system that acts as a reminder, urging payment a day or two before it is due. We note that these systems were in place for the pilots, but some focus group members expressed that they would like an improved system (or they did not get the notifications, e.g., because the phone attached to the account may be different than the one they regularly use).

b. **Balance checks:** Some focus group participants expressed that they would like a simple system to check the current balance, allowing them to reduce the effort for remembering when and how much to pay.

3. **Ownership transfer:** There were lively discussions in the focus groups about the desire for secondary markets where partially-paid systems could be transferred by the original owner to a new owner who would take over the loan payments (allowing them to recoup part of their investment). Two necessary conditions were mentioned for this: balance checks (see above), and a way to verify and transfer the account from person to person.

4. **Theft protection:** People were interested in the idea that stolen PAYG systems could reported by them and remotely shut off to reduce their value to thieves. Theft is a key concern for off-grid solar customers: our survey showed 40% of PAYG customers actively manage their solar module (moving it inside at night), with security being the most commonly cited reason.

**PAYG Economics**

PAYG combines market fundamentals from several intersecting areas: global supply chains for electronics, rural distribution networks, mobile money payments, and international financing. Bringing together insights from the broader market with focused effort on understanding PAYG we identified a number of core features that should be understood by entrepreneurs, policymakers, regulators, and supporting organizations.

**Risk Profiles**

PAYG provides a reduction (and in some cases elimination) of some of the risks that are often cited as barriers to off-grid power, but it also leads to other shifts in the overall risk profile of the market. Many PAYG firms face a number of additional risks that require unique management strategies for sustainable business in these markets.

**Currency exchange risk** can become a significant concern for any business model that provides credit to consumers. Some companies in other sectors often chose to mitigate the effect of local currency value by only borrowing capital from local banks. However most PAYG providers have been unable to exclusively source local capital. Furthermore, when inventory is ordered long in advance of sale, currency risk remains a problem, as prices are typically negotiated in US Dollars. Therefore, PAYG companies need to price the expected changes in currency into the retail prices charged to customers in order to maintain sustainable revenues and make debt and equity payments to investors, or face potential losses.
In the foreign exchange figure we show a range of representative currency exchange rates from countries relevant to PAYG solar. While the majority of fluctuations have been small and require little effort from companies, the three year period ending in 2013 demonstrates the potential for shocks in foreign exchange markets (FOREX). Furthermore, not all PAYG providers will be equally affected by such changes in exchange rates. Providers of lower-cost (and lower power / service) products, with short repayment terms (in the weeks-months range), would be least affected and can easily incorporate the expected currency fluctuation into the product price. For firms with product loan tenors exceeding a year, the risk becomes greater but still manageable through price adjustments or through the use of a debt service reserve account in the case of short-term extreme currency fluctuations. For developers of large household level or community mini-grid projects with PAYG components, the risk of significant currency exchange rate fluctuation during the life of the project is fairly high. In this case, debt service reserve accounts, currency hedges, and other mechanisms may be necessary to reduce the risk of losses.

![Foreign Exchange over 3-year period](image)

Fig. 22. FOREX for representative currencies, normalized so the ratio with USD at the beginning of the series is 1.

As with any financed product, PAYG providers face potential consumer default. Through our research, we identified three key factors that affect default risk for PAYG companies:

1. **Quality of technology:** For PAYG products, the quality of lighting technology becomes critical in avoiding consumer default. If the product fails before the loan is fully repaid, the consumer will cease payments until the item is replaced. Furthermore, if the time to replace a failed product exceeds expectations, customers may refuse to pay and move to a different product or a different provider. Finally, if product failure occurs after the loan is repaid but before the official warranty period ends, the consumer may lose trust in the provider and may decide not to purchase other products from the same company. Thus, product quality becomes paramount not only in generating revenue but also in the ability of the PAYG provider to scale past the initial product offering.
2. Changing ability to pay: Most PAYG providers conduct an informal credit check of every consumer, either at the point of sale or by phone following an initial inquiry. Such surveys often include self-reported information about income, property ownership, housing type, family size, level of education, and other factors. While this information is very useful to eliminate customers who clearly lack an ability to fulfill debt obligations, the majority of credit checks are yet unable to accommodate or predict the impacts of seasonal or unexpected fluctuations in income for all customers. For example, if part of the consumer base of a PAYG product is involved in coffee farming in Kenya and global commodity prices drop like they did in 2013, then a large proportion of paying customers may lose the income they need to finish repayment on their loan.

3. Tampering and theft: PAYG technology is relatively new, and while most products attest to being tamper-proof, experience with other measures such as DRM on DVDs or manufacturer locks on mobile phones suggests that tampering can occur among widely used IT-enabled services. However, it is important to note that none of the providers we interviewed indicated that this was a significant risk to their business based on early experience with the market.

Many PAYG providers have cited concerns around policy risk, like mobile currency regulations in the markets in which they currently operate or target countries for expansion. While Kenyan PAYG companies have seen a lot of success, it is unclear whether or not they will be easily able to adapt to new country regulations as they expand. This is particularly true for models that depend on a specific type of mobile currency, such as M-Pesa, which although widespread, has not seen the same level of global penetration as it has in Kenya.

As with any business that is not vertically integrated, there are partner risks for most PAYG firms. Thus far, most PAYG providers of GSM-enabled systems have created strong partnerships with mobile telecommunications giants to support their efforts. Fenix International and Nova Lumos both work exclusively with MTN in Uganda and Nigeria, while M-KOPA has partnered with Safaricom in Kenya. While this model has certain advantages, the potential risks are worth noting.

Since PAYG providers are relatively small entities thus far, they may have little bargaining power when it comes to determining transaction costs for mobile money transfers. Thus, if an operator chooses to raise rates—with significant implications for the overall price a customer will have to pay for a PAYG product—the PAYG provider can do little to avoid the resulting losses in customers or margins. Furthermore, if the single partner telecommunications company experiences technical issues resulting in dropped or delayed
payment transfer and the PAYG provider is dependent on the network for payments, there can be losses incurred and customer confusion if no other means of payment are available and products become disabled.

While partnership with a single telecommunications provider in a country like Kenya, where Safaricom holds significant market share, can be acceptable initially, the limitations become more serious when scaling or when operating in a more diverse market. Being limited to a single telecom partner can limit market penetration and potentially deny access to willing and able consumers. Furthermore, depending on the mobile money service, it is possible that there is some self-selection bias amongst different income tiers of consumers, thus limiting the total socioeconomic impact that a PAYG provider has.

DOWN PAYMENT
While consumer financing reduces the up-front cost barrier significantly, the initial down payment that many PAYG companies charge can still be prohibitive for marginal consumers. With the M-KOPA system, the ~3,000 KSH deposit that is currently charged for the M-KOPA III system is equivalent to the monthly income of many off-grid consumers. These deposits protect the firm from losses and are a barrier to entry that limits the participation of poorer customers. Improvements in the scoring approach that PAYG firms employ to select potential customers (based on the valuable data generated by a growing number of repayment data streams) could lead to a reduction of the down payment from improved views on default risk and even further improvements in market access.

COMPETITION AND MOBILE MONEY MARKET SHARE
Mobile money fees play a role in the ability of any individual product to compete in the market. For example, in Kenya, many PAYG providers employ M-Pesa Paybill (the dominant mobile money system) for all of their payments. It is advantageous to use Paybill because it is a service that offers the ability to have unique accounts associated with a repayment stream, enabling users to pay for multiple accounts using the same phone number. Paybill fees are negotiated individually with each firm (without standard fee structures), providing space where firms can gain retail cost advantages over competitors. This friction in the market can create distortion. The mobile money fees also present the opportunity for exercising a degree of retail market power by telecom providers that process payments and also co-brand or offer a PAYG system through their business (this has not been identified in the market thus far; it is raised here to provide clarity to the dynamics between mobile money and digital financing more broadly). The paradox is that it is attractive from one perspective to enter a PAYG market where there is a single, dominant, widely adopted mobile money platform to reduce the up-front cost in IT system setup and integration. However, a single telecom operator also

Fig. 24. One of the ubiquitous M-PESA agent locations in Kenya
exposes firms to risks from fee changes (depending on the agreement structure) and potentially competitive disadvantage in fee negotiation if the telecom is partnered with another firm or offers its own PAYG product for sale.

**UNIFORM PRICING**

Beyond payment platforms, the harmonization of pricing across regions or nations (i.e. you pay the same regardless of whether you are in an urban center or a rural village) has important implications for reaching outlying areas. Since pricing and margins are fixed, the sales agents cannot charge more in rural areas to cover the additional (and real) transportation costs to reach them. For rural consumers, however, this also has an upside of preventing double marginalization (i.e. raising prices to maximize retail-level profit) by resellers or agents who may hold a local monopoly on distribution in an area. Providing support to rural sales agent networks in support of distribution in sparsely populated areas could be an area of focus for market transformation efforts to ensure PAYG reaches both the rural and urban poor.

**ACCESS TO WORKING CAPITAL**

Like the broader off-grid solar market, one of the core barriers to scaling PAYG is access to working capital financing. Access to working capital allows PAYG providers to stock more product in-country, supply larger inventory to retailers and agents, and extend better loan terms to consumers. All of these factors ultimately contribute to higher levels of access. At this point, investment in the PAYG sector has been insufficient to fulfill capital needs for providers. Although more than $70 million of equity, debt, and philanthropic investment in PAYG firms has been publicly announced (originating from over 60 unique investors), a recent report by the Global Off-Grid Lighting Association (in 2014) cited a sector-wide need of over $1.5 Billion of investment to support consumer finance over the next 2 years. Bridging this gap will be crucial for growth in PAYG and the broader market.

**SOCIAL AND FINANCIAL RETURNS**

There is still a no common framework for assessing the performance of PAYG firms providing service to the market, particularly for investors and organizations trying to measure social impact and the financial profile of PAYG investments. In some cases the lexicon of the mobile phone industry is borrowed, with average revenue per unit reported. In other cases the descriptions are along financing lines with default or total repayment rates for systems offered as a loan (i.e. the fraction of expected payments received). Conversations with PAYG firms thus far have revealed that about 90% of the expected payments are eventually received, and higher rates are often reported publicly (e.g., M-KOPA reports a 95% repayment rate). There is an important distinction however between the micro-loan repayment rate and system activation rate (in other words, the fraction of solar home systems that are not deactivated).

While the repayment rate is important for financial returns, it is the system activation rate that determines the degree of energy access provided, and it is inevitably lower than repayment rates due to system deactivation after partial payment. As an example of how the difference plays out in practice, consider the overall results from repayment for roughly 650 customers in the SunnyMoney sales trial: For these customers, 90% of the expected payments were received but only 80% of customers were left with an activated lamp. That 10% gap...
represents customers that made some payments but did not fully repay. It is important to note here that those customers did receive energy service during the time when payments were made, so the loss is not complete (kerosene spending would have been offset during that time), but there is a missed opportunity to recover additional payments and put stranded solar energy assets to use.

One solution for companies to increase repayment and redeploy assets is to formalize and ease the transfer of stranded assets between consumers in secondary markets. While in theory the PAYG firm can often repossess systems that are not fully paid, it may be cost prohibitive (depending on the size/resale value of the system) and difficult from marketing and communications perspectives to redeploy previously used systems in retail markets through normal sales channels. Focus group participants indicated that clear processes for ownership transfer on a secondary market would be valuable. They emphasized that a critical element to make the system work would be having easy ways to verify the remaining balance (so negotiation on a price to transfer could occur, potentially allowing the original owner to recoup some investment) and to verify the transfer of the account from one individual to another. With the proper controls around identity fraud, the new owner could repay the system and ownership could be transferred to that person at full repayment. Such a system could also benefit the retailers of PAYG products, who often make much of their commission only after the full repayment of the product.

**DATA PRIVACY AND UTILIZATION**

Data is a key component of many PAYG business models, with substantial improvements over the status quo in visibility on repayment behavior and often also system-level monitoring. People in the focus groups voiced reasonable concerns about their personal privacy while also recognizing the value in these types of data.

A clear distinction was made regarding when and how the data could be used: the people we heard from approved of operators using data to improve consumer experience or business operations but they disapproved of the data being sold to third parties wholesale, regardless of the intended purpose. As one focus group participant elaborated:

"It’s good when the company keeps track of the payments and charging…so the lamp can be improved. Recording that information is like being closer to users (and lets the company understand the experience)...but I would not advise the company to give out the information because it might be misused." – focus group participant A (summarized from translation)

"If another party wants to have the data, they should sell their own lights, and get to know us." – focus group participant B

Their concerns about misuse stem from a range of issues: One that came up in the groups was M-Pesa fraud, a confidence scheme where someone will defraud a person by “accidentally” wiring them a small amount of money, then asking for the money back…they then say that the refund was not received and ask for a re-try or may raise the stakes. People had concerns that PAYG customers may be sensitive targets for scams that involve the system, if personal data are released.
Another potential misuse that was raised was those that obtain the data may use them harm the market share of SunnyMoney or create “fake” products. Customers in the focus groups felt a sense of connection with the PAYG offering firm (in this case SunnyMoney), and wanted to protect the organization. The people in the focus groups recognized that their market data were valuable, and expect confidentiality and security with them.

A final concern was over the potential for remote surveillance based, which could be used to identify the patterns of travel for people who use the system. Such a concern has been raised in the developed world with “smart” electric meters as well, where concerns include the potential for burglary of homes or other nefarious activity.

Customer concerns about data sharing do not necessarily preclude many of the ways PAYG operators are deploying them, but highlight the need for clearly communicated expectation. Consider the case of PAYG payment streams used to develop credit histories. This process is standard in many developed economies where most repayment streams on loans (and other bills) are provided to credit scoring companies, such as FICO, Experian, Equifax, etc. Credit scores are being used already in Kenya through the M-Shwari micro savings and loan service that is offered by SafariCom through the M-Pesa platform, which has been adopted by over 15% of the country (with 30% of those adopters using the loan features). While the practice of credit scoring is generally accepted for loans, utility bills are often not subject to reporting (at least, in the U.S.A. context). If PAYG is treated and viewed as a utility by the customer—consider firms offering a DESCO model or very long loan tenors—different expectations around the implications of non-payment on future offers or credit history could be appropriate. In either case, clear communication on the benefits and mechanism for access to additional finance with support from PAYG could prove to be sufficient.

As information and communication technologies (ICTs) are integrated throughout the energy system—both on and off the grid—there will be new opportunities and challenges around data management, privacy, ownership, and control. The status quo is for data to be protected and mined primarily by private sector system owners, operators, developers, and integrators, who may extract different value from the data by keeping it confidential and scarce (e.g. by encouraging repeat customers or improving their competitive position with product design improvements). Public uses of the data are important as well (e.g., better informed policy).

The full value from global data sharing and appropriate investment in data collection can only occur if sufficiently high fractions (or good samples and standardized aggregations) of data are available and sufficiently protected to prevent the need for over-aggregation and loss of value. Ownership of distributed energy usage data generated by dispersed global institutions, corporations, and citizens is a critical and unresolved legal and political issue that will continue to be important for the PAYG industry as it is with other IT-related firms.

**SUPPORTING A ROBUST PAYG MARKET**

Based on evidence from the field, we are optimistic about the potential for PAYG to accelerate energy access through a doubling or tripling of reach into the market (roughly the bump in sales of entry-level lamps by converting to PAYG). The amplification factor may be
higher among more costly systems, where financing needs are larger. These vital services help the rural poor climb the household energy ladder toward more equitable and climate-friendly electricity\textsuperscript{19}. Furthermore, the basic PAYG business model (with assets in the field that can back and enforce loans) could be a foundation on which to build access in other critical areas: higher-power appliances, clean water, health, and other areas where loans and technology investment can change lives.

**Some key next steps and drivers of change we identified in our work are:**

*For Lighting Global and Lighting Africa:*

Support PAYG products with Quality Assurance verification that is appropriate to continue risk reduction from product quality issues, with emphasis on supporting verification of the special or added features of IT-connected energy systems (underway).

Continued work to identify and support solutions to targeted market needs for the PAYG sector of off-grid power, like those listed below (underway).

*For the Public Sector:*

Find ways to leverage the connectivity of PAYG systems for effective and inexpensive tracking of system reliability for conformance with service standards, carbon credits, project requirements, etc.

Build support and outreach for PAYG firms into energy access plans.

Integrate energy access planning with telecommunications and mobile money / financing, where possible.

Reduce trade policy barriers that impact solar products broadly, such as value-added tax and import tariffs

*For Investors:*

Provide low-cost appropriate capital, which is a limiting factor to growth in this important market. There are particular needs for debt funds to support loan and service offers.

Work with companies to develop standard metrics, allowing for receivables-backed financing and a shift towards securitization

*For the off-grid solar power industry:*

Provide high-quality solar power systems for a growing PAYG-enabled market with partnerships and new ventures.

PAYG can be integrated in existing supply chains along side cash sales, growing and strengthening the connections with sellers and supporting communities with improved access.
Adopt best practices in securing customer data while still making data available for effective use of insights that lead to better energy access. Clearly communicate how repayment and system use data are used and controlled.

*For telecommunications and IT*

Provide standardized application programming interfaces (API) for integrating into mobile money systems to ease PAYG platform scaling.

Reduce transaction fees for basic needs service payments and provide a standardized fee structure with easy start-up for new services.

Find ways to support robust competition in the energy market to maximize the reach of off-grid power. Early connections to solar electricity provide basic needs service: critically important lighting and recharging for IT devices like phones and tablets.

Continue supporting interdisciplinary research (e.g., through GSMA M4D) and collaboration across sectors to learn and support best practices.
CHAPTER 2 REFERENCES


ANNEXES TO CHAPTER 2

About Lighting Global

Lighting Global is the World Bank Group’s platform to support development of commercial markets for modern energy services for the more than 1.2 billion people in the world without access to electricity. Through Lighting Global, IFC and the World Bank collaborate with the Global Off-Grid Lighting Association (GOGLA), the solar energy services industry and development partners to spur growth of markets for clean, affordable, modern energy services.

The Lighting Global product quality assurance program sets the global standard for quality off-grid solar devices and kits. The program presently lists over fifty quality-verified solar products from more than 25 manufacturers. The Lighting Global platform provides support to a broad portfolio of country-based regional market development programs - Lighting Africa, Lighting Asia and Lighting Pacific, which work along the supply chain to reduce market entry barriers and first mover risks in key off-grid solar markets.


About IFC

IFC, a member of the World Bank Group, is the largest global development institution focused exclusively on the private sector. Working with private enterprises in about 100 countries, we use our capital, expertise, and influence to help eliminate extreme poverty and boost shared prosperity. In FY14, we provided more than $22 billion in financing to improve lives in developing countries and tackle the most urgent challenges of development. For more information, visit www.ifc.org.

About the World Bank

The World Bank, a member of the World Bank Group, is a vital source of financial and technical assistance to developing countries around the world. Our mission is to fight poverty with passion and professionalism for lasting results and to help people help themselves and their environment by providing resources, sharing knowledge, building capacity and forging partnerships in the public and private sectors. For more information, visit www.worldbank.org.


NOTES ON M-KOPA APPROACH
The M-KOPA system, the D20g, at the time of this research had the following pricing strategy: 3000 Ksh down payment and 50 Ksh a day for 360 days—for a total of 21,000 Ksh, or about $30 down, $0.55 a day, for a total of $230. After this period the system is owned outright. If someone fails to pay the system will not work until they begin payments again. Payments can be made with any frequency, but typically are done on a weekly or monthly basis by users due to income stream fluctuations and mobile money transaction fees.

The payments are made through M-Pesa mobile money and the systems have integrated GSM modules, allowing them to be activated remotely once a customer’s payment processes.

M-KOPA has over 100,000 systems in the field since their inception and has a goal of 1 million by 2018. They started in Kenya and are expanding to Uganda.

The M-KOPA sales agents network has schemes for offering credit to agents for purchasing stocks, along with incentives that come on the initial purchase (600 Ksh) and on payoff (600 Ksh). The total margin is therefore 1200 out of 21,000, or 6%. This is on par with the margins reported by retailers for broader solar goods. It is important to note that the M-KOPA approach does not require the same level of working capital financing for retailers, who pay significantly less than a typical wholesale price to carry M-KOPA stock (only the down payment for each system) and can build trust (and a line of credit) through repeated good business dealings and sales. The commission is not paid in full until the device is fully repaid, which places some onus on the retailers to select credit-worthy and trustable customers.

The cash payment for the system is 17,000 Ksh — $190.

NOTES ON SUNNYMONEY APPROACH
SunnyMoney tested two platforms for PAYG during our study period that accomplished essentially the same purpose: financing for an entry-level solar study lamp. The entire process was essentially integrated into a modified version of the “traditional” schools campaign model through their research/innovation unit, SunnyMoney “Brains”.

They chose to test two payment mechanisms (see information in main text) with total costs of 1200-1300 Ksh over a series of weeks. The payments were made either in cash to a sales agent or via M-Pesa, and allowed SunnyMoney to assess the logistics differences for each one. For both payment cannels, the sales agent then connects to the lamp with a smart phone and "activates it", collecting commissions of 30 Ksh on the initial down payment and 70 Ksh on payoff (for a total of 100 Ksh for financing the lamp, or 10% of the 1,000 Ksh retail price for a cash-equivalent model without PAYG).

The smart phone activation approach avoids the need for GSM modules that would cost roughly $10 on a wholesale basis – which would effectively triple the cost of entry-level lamps.

Through the pilot projects, SunnyMoney Innovation department (SunnyMoneyBrains) aimed to develop and test an affordable PAYG model for study lamps – combining ultra-low-cost
PAYG technologies with entry-level solar products to build experience and iterate on PAYG approaches for this segment of the pico-solar market.

Exchange Rates: Our field work took place primarily during May and June 2014. The exchange rate we use in our analysis is based on the average rate during this period, 86 Ksh / 1 USD (from Yahoo! Finance).

Datasets collected for this study: The datasets below were collected in support of this study and other related projects that were conducted in parallel. All the data were collected by or in collaboration with our research team. These datasets are supplemented by others that are publicly available or available through the Lighting Global program.

<table>
<thead>
<tr>
<th>Scale</th>
<th>Name</th>
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<tr>
<td>End-user</td>
<td>Telephone survey (0-1 months after purchase)</td>
<td>Buyers of PAYG systems</td>
<td>55 SunnyMoney Customers.</td>
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<tr>
<td>End-user</td>
<td>Telephone survey (4-9 months after purchase)</td>
<td>Buyers of PAYG systems</td>
<td>160 M-KOPA customers 45 SunnyMoney Customers (all from initial survey)</td>
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<tr>
<td>End-user</td>
<td>Focus Groups</td>
<td>PAYG purchasers through SunnyMoney Pilot</td>
<td>~ 40 participants in 4 groups. 2 each in two separate towns.</td>
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<td>Retail</td>
<td>Retail Survey</td>
<td>All retailers of off-grid lighting</td>
<td>~150 shops</td>
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<tr>
<td>National Distribution</td>
<td>Structured interviews</td>
<td>Managerial-level employees and executives at PAYG organizations</td>
<td>~ 5 each at M-KOPA and SunnyMoney / Angaza / divi. Non-disclosure agreements prevent release of sensitive aspects of the particular business models. Synthesized results in combination with the Global structured interviews are included in this study.</td>
</tr>
<tr>
<td>Global</td>
<td>Structured Interviews</td>
<td>Managerial-level employees and executives at PAYG organizations and other stakeholder firms (device manufacturers, telecommunications industry).</td>
<td>~ 15 interviews with anonymized and synthesized results reported that do not betray private details of particular business models.</td>
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Chapter 3

Quality Communication

Quality assurance in Kenya’s off-grid lighting market

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Available online: https://www.lightingafrica.org/resources/

Abstract:
The flow of information and goods defines supply chains for solar, like any electronic good. In this study we uncover the structure of flows for goods and information in the Kenya market with a focus on information about product quality and durability, a key factor for the economic, social, and environmental performance of off-grid solar. The basis for our research is a set of retail-level surveys (n=150) conducted in May and June 2014 (following up on surveys in 2009 and 2012 in the same locations), which is combined with solar customer surveys and structured interviews across the global industry, from capital cities to rural villages. We show how solar products with quality verified by Lighting Global flow through a range of supply chains that are parallel to and often separate from incumbent electronics goods supply chains. The structure of the business networks indicate (and our research confirms) the high value of reaching distribution-level buyers with information about product quality, since their purchasing decisions drive retail choice sets. At the retail level we identify new opportunities for reaching retail sellers through information technology (e.g., social media, mobile internet), but traditional channels (paper flyers, word-of-mouth, etc.) continue to be highly valued as well. Beyond active communication, there are also subtle and direct cues about quality available and utilized by buyers and sellers in the supply chain. These include branding around firms or technology, experiential accounts, and availability and placement of products in market settings.

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University (N.T.B. and A.J.), and the Renewable and Appropriate Energy Laboratory at University of California, Berkeley (P.A., D.G., and D.K.). Thank you to the survey and focus group participants, interviewees, and collaborating organizations in off-grid energy and telecommunications. We are particularly grateful for collaborations with SunnyMoney / SolarAid, M-KOPA, Angaza, and divi. In addition, we received expert advice and support in the field from our research team, particularly Maina Mumbi and David Mugo. Thanks also for valuable comments, suggestions, and conversations from our colleagues at Lighting Global, the Schatz Energy Research Center, and participants in seminars and workshops.
Executive Summary

Quality assurance (QA) is a core feature of Lighting Global’s support for the growing off-grid lighting market, and there is a recognized need for reliable information about product quality and performance as the market grows towards 10’s to 100’s of millions of users served. Fundamentally, QA is a process of ensuring that accurate and trusted information about product quality is available for those who need it: producers, buyers, regulators, and other market stakeholders. For example, Lighting Global's voluntary product testing leads to performance results that are published through a standardized specifications sheet that can inform the purchasing decisions of distributors and investors.
In this report we describe how QA information can be effectively captured and deployed throughout the modern supply chain. As the market evolves, there are new opportunities for strengthening QA activities. Our findings include new insights on the role of information and communication technology (ICT) access, the emergence of recognized brands and large distributors, and broader awareness of pico-solar.¹ The opportunities we identify build on the successful QA foundations of product testing and verification that are at the heart of the Lighting Global approach.

This work draws on a research effort from May through July of 2014 to understand the current dynamics of the off-grid lighting market in Kenya. An early target for the pilot of Lighting Africa, Kenya displays evidence of a shift from early-stage market entry to a more mature market for pico-solar. We sought to understand the ways that pico-solar is supported, distributed, and sold in markets like Kenya that could provide leading examples for the broader global market.

The market share of quality-verified² pico-powered lighting systems has dramatically increased in western and southern areas of Kenya over the period of support from the Lighting Africa program. Based on our research, pico-solar products now represent ~80% of the “electric off-grid lighting” market³ as measured by sales value, up from single digit percentages in 2009, and quality-verified products represent roughly 50% of the solar market. This rapid growth in market share for quality-assured solar and other solar products has been aided by support from the QA program and additional market support from Lighting Africa and other institutions, indicating a degree of success from these early market efforts. We found that QA verification is required or contributes strongly to decisions at several core points of the supply chain (e.g. buying requirements for large buyers) that manifest down the supply chain through the availability of good quality products and increased retail demand.

While QA is a complex set of processes, here we distil it into two core “flows of information” that work together to reduce uncertainty and risk in the market: monitoring quality so it can be understood and verified by high-level supply chain actors and institutions (like manufacturers and programs like Lighting Global), and communicating verified quality to buyers and other decision-makers in the supply chain. When both mechanisms are working well, buyers can trust

¹ In this report, pico-solar refers to solar lanterns and small (< 10 Watts) solar powered lighting systems that can include more than one light point, charge a mobile phone, or power a DC radio or fan.

² Products that meet the Lighting Global Minimum Quality Standards

³ Defined as energy devices that can at least provide lighting service, are sold on a retail basis in a complete package, and may include rechargeable batteries or require primary disposable cells (including torches / flashlights).
that the products they are purchasing will perform as advertised and provide a reasonable service life. We find that both elements of QA are at work in the market, closely linked with the structure of particular distribution channels and financing opportunities.

**KEY FINDINGS**

**Communicating Quality through the Supply Chain:** Our team explored several strategies that could enable Lighting Africa to improve its communication of QA information to consumers and supply chain stakeholders. These included radio advertising for consumer awareness campaigns, product specification sheets and flip books for distributors and retailers, and the use of electronic communication to connect with an increasingly digitally literate market. We found that specifications sheets and clearly designed flip books were preferred by both retailers and distributors as tools for conveying quality information to buyers.

**Signaling Quality to Buyers:** We investigated both “traditional QA” quality signals (e.g. product specification sheets and on-the-box performance reporting) and non-traditional quality signals like warranties and consumer financing. We found that on-the-box reporting and online communications were the preferred means of communicating quality information for distributors. Actionable warranties and pay-as-you-go (PAYG) financing can also serve as quality signals for buyers, since they spread the risk of early failure more equitably between sellers and retail buyers. A combination of these mechanisms for signaling quality to buyers is present in the market, with the mix of information evolving along with the broader market.

**Building Brands:** A core feature of the way retailers and customers recognize good and bad quality products is through brand-recognition and brand-loyalty. Notably in Kenya, the d.light brand (and particularly the S2 model promoted heavily by d.light and SunnyMoney) is widely recognized on a retail level. We also identified a number of “counterfeit” products in the market that look very much like the ubiquitous d.light S2 but with different branding, responding to the form factor loyalty that has been created around the product. Distributors and retailers in the Kenya market attribute the success of d.light S2 to early adoption through broad institutional sales (it was the core model sold by SunnyMoney schools programs for a critical period of market growth), broad advertising efforts, and low price points.

**Availability and Choices:** The wide distribution of quality-verified products in distributor, proprietary, franchise, and NGO distribution channels is based on reaching key decision makers higher up the supply chain with QA. Over 63% of retailers cited distributors as the main source of information about new products. Decisions made by distributors ultimately determine the products and opportunities for comparison shopping that are available to end-users, indicating that distributor and retail networks should remain a core focus area for QA engagement. We did
identify one sales channel with a notable absence of products that meet the Lighting Global quality standards: the large, legacy wholesale traders in Nairobi that import electronics goods to Kenya. While specialty distributors that focus on pico-solar have been central to the market's growth, the wholesaler traders could play a unique role in facilitating the large-scale distribution of solar products to small retailers from rural areas through existing channels.

The Importance of Nimble QA: One of the biggest challenges facing pico-solar products is the fact that they are essentially consumer durables in competition and co-mingled with fast-moving consumer goods (FMCG) like kerosene lamps or torches. Pico-solar sales have increased dramatically in distribution channels where creative distribution and financing strategies allow customers to access and purchase pico-solar products more like an FMCG. Traditional QA for electronics is focused on the consumer durables market, and for QA to support rapid growth in pico-solar there need to be “nimble” strategies for monitoring and communicating quality that can scale with and respond to the market. Accelerated testing and novel avenues for verifying quality should continue to be priorities for QA support of the market. For example, products employing mobile connectivity for PAYG can also capture remote in-field monitoring to verify ongoing product operation and offer responsive after-sales support.4

KEY OPPORTUNITIES

While a variety of opportunities were identified for improving the flow of quality assurance information through the off-grid lighting supply chain in Kenya (please see Conclusions and Recommendations), the following three opportunities were identified as having the highest priority for current quality assurance efforts:

1. Create simplified specification sheets with product performance results that can be accessed easily on the Lighting Global website for each product, and encourage manufacturers and distributors to reference and disseminate the print matter when interacting with vendors. Also explore the publication of an illustrated flip book that explains how solar technology works, what the benefits are, how to maintain solar products, and how to service a warranty. These flip books could be shared with distributors to facilitate training and promotion higher up in the supply chain, and they could also be piloted among select retailers to test their impact on sales.

2. Create a Lighting Global or Lighting Africa Facebook page with information for distributors, retailers, and consumers. In addition, the Lighting Global and Lighting Africa websites should be made compatible with smart phones, starting with the product page.

3. Engage with wholesale traders in Nairobi’s markets where many of the low-level retailers source their products. Increasing the presence of solar products in such areas could significantly improve comparison shopping opportunities for consumers further down the supply chain.
Quality Assurance for the Off-Grid Market

For most countries belonging to the Organization for Economic Co-operation and Development (OECD), quality assurance (QA) and warranty mechanisms are safeguards that operate in the background of the modern manufacturing and sales industries. Although the average consumer is scarcely aware of them, certifications from the Underwriters Laboratory (UL) or trade associations ensure that the products that make it to market are safe and in compliance with a variety of national and international quality standards. In addition, customers are generally able to return faulty products for repair, exchange, or refund, although the quality of response can vary. An effective QA framework therefore employs three distinct mechanisms for protecting consumers: voluntary or compulsory product testing, a reliable warranty program, and repercussions for poor quality products or poor warranty servicing. Product testing serves as a preventative measure to protect consumers from low-quality products before they make it to market. However, if low quality or unsafe products are sold to consumers, the company can be held accountable through a warranty program, legal repercussions, or the rejection of their brand by consumers. Thus product testing, warranty servicing, and legal repercussions must work in tandem as institutional mechanisms in order to effectively safeguard consumer interests.

Figure 1: Left: countries belonging to the Organisation for Economic Co-operation and Development (OECD); Right: non-OECD countries.

But what about non-OECD countries? What does quality assurance look like in markets where product testing, legal enforcement, or consumer protections are underdeveloped? How can companies be held liable for low-quality or unsafe products where there is little brand-recognition or where access to information about product quality or performance is limited?

Given the particular constraints facing off-grid lighting markets, Lighting Global has developed a QA framework that includes rigorous testing for products before and after they reach the market and various mechanisms for communicating information about product quality and performance to buyers, retailers, investors, and other market stakeholders. The overarching goal of the QA framework is to support good quality products and prevent market spoilage from bad buying experiences. This approach seeks to increase the visibility of high quality...
lighting products in the market while helping individuals and businesses in the off-grid lighting supply chain make informed decisions about the products that they are purchasing.

Currently, Lighting Global has four distinct mechanisms for communicating information about product quality and performance: engagement with manufacturers, distributors, and other key market stakeholders in the supply chain, regional consumer awareness campaigns, product specification sheets and technical notes on the Lighting Global website, and on-the-package reporting and labeling requirements. This report will attempt to characterize the flow of QA information in Kenya's off-grid lighting market and identify key opportunities for improving QA information access throughout the supply chain.

STUDY METHODS
This research was conducted in five different counties in Kenya from May through July of 2014. Kenya was chosen because it is one of the market leaders for pico-powered lighting systems (PLSs) in Africa, and because the Lighting Africa program originally started in Kenya in 2007. This study also draws from years of experience developing and operating the Lighting Global Quality Assurance program. In order to map the flow of products, information, and finance through the off-grid lighting supply chain in Kenya, our research team partnered with several NGOs and businesses to collect over four hundred surveys from consumers, retailers, distributors, finance providers, manufacturers, and non-profit organizations. Surveys were conducted in-person across Kenya, Germany, and the United Kingdom, and over the phone from the United States and the United Kingdom. We conducted these key informant interviews across the supply chain for off-grid lighting, from global head offices to regional distribution houses (interviewing approximately 30 individuals). We also undertook detailed in-person surveys (approximately 130) at the retail level for sellers of both quality-verified and unverified off-grid lighting products. This mixed methods approach gives our team unique insight to the contemporary market, particularly in Kenya. In addition, we partnered with SunnyMoney (58 pico-solar customers) and M-KOPA (170 solar home system customers) to gather information related to pay-as-you-go (PAYG) financing and digital literacy among their customer base. Finally, we conducted two focus groups with SunnyMoney customers to learn more about what customers think of PAYG financing and data collection from PAYG devices.

The Off-Grid Lighting Supply Chain
While each product follows a particular path from the factory to the end-user, that path can depend as much on the flow of finance and QA information as it does on transportation infrastructure. Where products, information, and finance flow freely through the supply chain, supply chain actors are able to comparison shop, make informed decisions, and ultimately access the products and services that they need and want. In this sense, the flow of products,
information, and finance are critical for understanding the various facets of energy access. Figure 2, below, captures the flow of products from their origin in Nairobi to their sale in urban, peri-urban, and rural markets.

Figure 2: Distribution channels observed in the off-grid lighting supply chain in Kenya. The blue lines represent the flow of products that have met the Lighting Global quality standards; the red lines represent all other off-grid lighting products (including torches, key chain lights, emergency lights, etc.); and the yellow line represents the flow of counterfeit products. Gradations within the color scheme represent the confluence of different product flows (orange: unverified and counterfeit products; purple: quality-verified and unverified products; pink: quality-verified, unverified, and counterfeit products). Line width approximates the quantity of products flowing through each channel based on market observations and interviews with retailers, MFIs, and distributors for the three towns and the Nairobi wholesalers market that were surveyed. The product flows indicated may not be fully representative of national sales volumes for each category if sales in other regions differ from those in the regions covered in this study.
Table 1: Six primary distribution channels in the off-grid lighting market.

<table>
<thead>
<tr>
<th>Supply Chain Classification</th>
<th>Central Organizing Actor</th>
<th>Other Key Actors</th>
<th>Example</th>
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<tr>
<td>Non-Governmental Organization (NGO)</td>
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<td>Institutional partners, global manufacturers</td>
<td>SunnyMoney and Kenya public schools</td>
</tr>
<tr>
<td>Wholesale Distributors</td>
<td>Headquarters offices, global manufacturers</td>
<td>Institutional partners</td>
<td>SolaTaa</td>
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<tr>
<td>Wholesale Traders</td>
<td>Regional distributors and retail networks</td>
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</tr>
<tr>
<td>Proprietary Channels</td>
<td>Global manufacturer or private company</td>
<td>Retail channel partners</td>
<td>d.light or M-KOPA</td>
</tr>
<tr>
<td>Franchise</td>
<td>Global retail chain owner</td>
<td>Global manufacturers</td>
<td>Total petrol stations</td>
</tr>
<tr>
<td>Microfinance</td>
<td>Microfinance institution (MFI) or Savings and Credit Cooperative Organizations (SACCO)</td>
<td>Global manufacturers, regional distributors</td>
<td>Rafiki, K-REP, or Unilever SACCO</td>
</tr>
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</table>

**Six Core Sales Channels**

We identified six core channels through which pico-solar products were distributed in Kenya (summarized in Table 1). This investigation confirms previous findings that the majority of solar lighting products flow through distributor and retail channels, with most off-grid lighting products flowing through wholesale traders and wholesale distributors first and then being sold to end-users by retailers. A fraction of lighting products are sold through franchise distribution channels like Total petrol stations. In addition, family members can play an important role in conveying products from urban or peri-urban markets to relatives in rural areas. A large number of quality-verified products are sold through proprietary and NGO-partnership channels by companies like SunnyMoney and M-KOPA. SunnyMoney notably sells more solar lights in Africa than any other company by combining institutional sales through

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6 The distinction between wholesale traders and wholesale distributors is imprecise, but for the purposes of this investigation, wholesale traders are defined as shop owners in Nairobi who source products directly from manufacturers to sell primarily on a wholesale basis. The majority of wholesale distributors are also located in Nairobi, with some notable exceptions located in Mombasa, and source products directly from manufacturers. However, wholesale distributors typically have formal contractual agreements with a small number of manufacturers and also participate in the marketing and distribution of those products to sub-distributors and retailers.

7 Retailers include traditional brick-and-mortar shops as well as informal tables or sidewalk hawking. Retailers are generally stationary and located in urban or peri-urban contexts, whereas village-level entrepreneurs sell products at open-air markets, churches, and savings groups in rural areas.

8 In the middle of 2014, M-KOPA transitioned from selling the d.light D20g, which was quality-verified, to selling the M-KOPA III, which is not currently listed on the Lighting Global website.
schools with a developing network of sub-distributors that sell through traditional brick-and-mortar retail shops. With a few exceptions, microfinance institutions (MFIs), savings and credit cooperative organizations (SACCOs), and supermarkets do not move a substantial volume of product.

It is important to note that, while the channels for distribution have not changed significantly in the off-grid lighting supply chain as it has evolved, the types of products and the volume of sales through each channel continue to evolve as the market develops. In particular, Figure 2 captures the flow of three distinct product types in Kenya’s off-grid lighting supply chain. First, there are some forty-seven different pico-products available on the market that have been tested and have met the Lighting Global quality standards. The second category captures all other off-grid lighting products, including dry-cell torches, grid-charged emergency lanterns, key chain lights, and even non-verified solar lanterns and solar home systems. The final category is actually a unique subset of unverified products: the counterfeit products that have proliferated as successful solar products gain enough popularity to merit mimicry.

INFOmATION FLOw IN THE SUPPLY CHAIN
Access to information about product quality and performance plays a central role in the development, marketing, and sale of off-grid lighting products. When information flows freely up and down the supply chain, investors and buyers are able to make informed investment and purchasing decisions, and manufacturers are able to develop and improve product design based on customer feedback and outcomes from the field. In the absence of information about product quality or durability, investors and buyers must rely on direct experience or anecdotal evidence, often arresting the introduction or adoption of new or unproven technologies like solar lanterns. Market spoilage, which was documented in the early development of the Kenya market, occurs when consumers lose confidence in a new technology based on bad experiences with poor-quality products or when manufacturers are disconnected from the realities of how their products perform in the real world.

As a consumer protection mechanism, the flow of information about product quality and performance can be as simple as a word-of-mouth recommendation and as complex as an international quality standard enforced by government regulators and inspectors. In both cases information can reduce risk and uncertainty for buyers and consumers by addressing the central QA questions: Will this product perform as advertised? Will it last? Is it worthy of investment?

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9 Please see www.lightingglobal.org/products for a current and comprehensive list of all Lighting Global quality-verified products. Not all forty-seven products are available in the Kenyan market.

INFORMATION MEDIANS
Despite sharing the same goal, not all information mediums are created equal. A television advertisement may reach a broader audience, but it does not carry as much weight as a personal recommendation from a trusted acquaintance. For pico-solar products, advertising and promotion through media or on-the-box labeling requirements can help increase consumer awareness, but they may not carry the same weight as word-of-mouth referrals, product demonstrations, or product presence in a trusted retail shop.

The rapid development and proliferation of information and communication technologies (ICTs) like mobile phones and internet services is also creating new channels for quality assurance information to flow more dynamically within the supply chain. A key finding of this investigation is that information and communication technologies like mobile phones and social media apps can simultaneously expand the reach and impact of QA information by grafting impersonal, institutional messages into personalized, relational networks that carry weight with end-users. Combined with the increasing digital literacy of rural customers, the channels for information flow that have been opened up by information and communication technologies represent one of the most important opportunities for improving quality assurance in the market.

REDUCING UNCERTAINTY VS. REDUCING RISK
Despite the increased presence of ICTs, off-grid markets are still particularly vulnerable to information asymmetry, a market failure that occurs when buyers know less than sellers about the quality or performance of products in the market. Given the uncertainty or risk associated with the investment, a buyer must rely on a variety of sources and signals to determine the product's relative quality or utility. While some of these signals reduce uncertainty by indicating how the product performs or how suitable the product will be for the buyer's needs, other signals reduce risk by indicating the product's quality or durability.

For the purpose of this report, signals that reduce uncertainty will be characterized as either direct or indirect. Indirect signals like product presence, branding, or word-of-mouth referrals are sources of information that cannot be controlled by the seller but still inform and influence consumer behavior. Direct signals like advertising, on-the-box reporting, and sales tools are sources of information that require a specific action or effort on the part of the seller. While both indirect and direct signals reduce uncertainty by communicating information about the product (e.g. its utility, desirability, or performance), this information is not always a reliable indicator of quality. Thus, quality signals like quality seals, warranties, or consumer financing play a unique role in reducing risk and safeguarding consumer interests in off-grid markets.

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Given the complexities of product and information flows in the off-grid lighting supply chain, an effective QA program must employ a variety of strategies for monitoring the quality of products and communicating QA information to market stakeholders throughout the supply chain. This report will consider the influence of QA information in Creating Quality (prior to market entry), Delivering Quality (impacts on product distribution and financing), Reducing Uncertainty through Indirect and Direct Signals, and Reducing Risk through Quality Signals. Finally, this report will conclude with a discussion of recommendations for the QA program going forward.

Delivering Quality

Quality signals like warranties or branding are useful for distinguishing higher quality products that are already available to end-users, but the majority of the most important decisions about product design, financing, and distribution are made long before a product makes it to market (see Creating Quality sidebar). Engagement with key market stakeholders—manufacturers, investors, government regulators, and distributors—is crucial for an effective QA framework because the decisions that are made at the top of the supply chain determine the flow of products, information, and finance through the rest of the supply chain.13

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As the gatekeepers to the market, these stakeholders not only determine which products are ultimately available to end-users, they also influence how those products are priced, presented, and serviced.

FINANCING
Investors and donors often use information about product quality and performance when conducting due diligence to determine whether or not a company merits support. As a result, QA information can play a significant role in determining which companies and products receive support through working capital, consumer-level financing, or social impact investment.

Access to working capital for distributors, sub-distributors, and wholesalers has an impact on how much inventory can be purchased and stocked. Since pico-lighting is more expensive and takes longer to turn over than dry-cell torches or kerosene, sufficient working capital is important for maintaining a consistent in-country supply. Given that pico-solar manufacturers often require up-front payment for production and shipping, and given an elastic demand that fluctuates according to seasonal income cycles, access to working capital is critical for ensuring a consistent market presence for pico-products. This is particularly true for firms that provide financing to consumers (see below), as low-income customer segments often require relatively long loan tenors.

Consumer-level financing can vastly improve product sales and penetration. Consumer-level financing is available in two distinct forms: pay-as-you-go (PAYG) arrangements where ICT-enabled payments are made in installments, and consumer loans made by micro-finance institutions (MFI), savings and credit cooperative organizations (SACCO), or hire-purchase and check-off arrangements. Consumer-level financing is particularly important for solar products like study lamps and solar home systems because the initial cost is often prohibitive for individuals and families with few resources.

Finally, impact investors and charitable donors are interested in product quality and salability, but they also want to ensure that the product will fulfill a particular social or environmental need. An excellent example of this is the study lamp form factor that now dominates the pico-solar market. While these small solar lamps are increasingly popular due to their low price points and flexible use as a torch or ambient light, their suitability as study lights for children doing homework also makes them popular with investors and donors. Although detailed measurements of social impact are beyond the scope of a QA program, pay-for-performance financing through

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14 One distributor indicated that the minimum turnover time is six months: three months for transport from China, plus three months for in-country distribution and sale.
social impact bonds or carbon markets could provide an attractive source of funding for high quality products that can be effectively monitored and evaluated.

**Distribution**

Distributors, NGOs, and franchises also depend on QA information and exert significant influence on the types of products that are available in the market. Taking into account the ease with which supply-chain actors are able to source low-quality products from generic manufacturers and circumvent customs inspectors with bribes or intra-Africa importing, engaging with product distributors and traders is critical for supporting the availability and movement of quality-verified products in the supply chain. In this way, the distribution channels that carry counterfeit and unverified products in Figure 2 indicate where information about product quality and performance is most needed.

![Image of a retailer selling a variety of electronic items](https://via.placeholder.com/150)

**Figure 3:** Example of a retailer selling a variety of electronic items. (photo: Maina Mumbi)

As an example, the fact that none of the wholesale traders that we talked to in Nairobi had heard of Lighting Africa or seen one of the product specification sheets underscores where quality assurance information is severely lacking: the wholesale markets in the Luthuli Avenue, River

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Road, Nymakima, and Kamukunji sections of Nairobi where almost 40% of retailers in Kericho purchased lighting products and other wares. In the absence of such information, it is likely that the flow of low-quality and counterfeit products through these markets will continue unabated.16

Connecting with wholesale traders is particularly challenging though, as there are many more traders than distributors in Kenya, and many of these traders are insulated from the repercussions of selling low-quality products because of the limited availability of QA information in the market and the inability of buyers to seek recourse when they have purchased low quality goods. As one trader put it, "No one [here] cares about quality. They just care about money." Another source of reluctance is due to the fact that, unlike other consumer electronics like stereos, fans, rice cookers, or televisions, many traders think that the retail market in Nairobi for solar products is smaller due to grid availability (even accounting for consumers who purchase products for off-grid relatives). Be that as it may, quality-verified products and solar products in general represent an increasingly lucrative opportunity for the traders who sell to rural retailers, and the wholesale markets can also play an important role in facilitating comparison shopping within the supply chain.

CONSEQUENCES OF QUALITY
There are two additional challenges facing pico-solar systems in Kenya. First, quality solar lamps are consumer durables (long lasting products) that are forced to compete with cheap, fast-moving consumer goods (FMCGs)17 like kerosene and dry-cell torches. Given capital constraints, most of the rural poor without electricity purchase domestic goods and energy services in small amounts at regular intervals. In Kenya, kerosene can be purchased by the deciliter (~3.4 oz) to fill inexpensive wick or hurricane lamps. Cheap, dry-cell batteries can be replaced in low-cost torches and key chain lights, and candles provide the least expensive lighting service when the previous options are not available. While pico-powered lighting systems provide a superior lighting service from a renewable energy source, the up-front cost of this service is often greater than what most rural customers can afford. Ironically, the very characteristic that makes pico-solar more attractive—quality—also raises the initial cost and makes it less accessible.

As a result of their greater expense, consumer durables like pico-solar products tend to be sold in urban and peri-urban markets that are less accessible compared to village-level markets where FMCGs are sold. For example, FMCGs like candles and torches are readily available at small village general shops (dukas), enabling consumers to purchase what they want, when they need it without having to travel too far from home. In contrast, consumer durables are

16 Given the vulnerability of quality-verified products to counterfeiting and the appearance of quality by many counterfeit products, it is not clear what impact the availability of QA information would have on the prevalence of counterfeit products in the market.

17 For the purpose of this investigation, FMCGs are defined as products that can be purchased in small quantities at regular intervals to provide a temporary good or service (shampoo or laundry sachet, soap, soft drinks, food items, etc.). Consumer durables are defined as products that provide a service for at least two years (e.g. fan, mobile phone, radio, television, etc.).
more expensive to transport and stock, and as a consequence they are less widely available. As a result, consumers are more apt to shop for consumer durables in urban or peri-urban markets where a greater number of shops offer more selection and better pricing.\footnote{Neuwirth, Benjamin. (2011) "Marketing Channel Strategies in Rural Emerging Markets."}

While the distinction between consumer durables and FMCGs is less important for formal distribution channels such as NGOs, franchises, and proprietary supply networks, the impact on retailers is still significant. Almost 40% of the retailers in this study went to Nairobi to purchase their products. Many of these retailers purchase from the wholesale electronics markets where they can comparison shop, receive wholesale prices for small purchases, and pick up other FMCGs for their shops. In contrast, sourcing solar lights from wholesale distributors is considerably less convenient. Wholesale distributor offices are often scattered around Nairobi instead of located in a central market, which results in greater travel costs for small business owners seeking inventory. Minimum orders to qualify for wholesale pricing or free transport are often prohibitive for smaller retailers. And the fact that most distributors carry only one line of products makes it difficult to provide greater variety to customers. In other words, another consequence of higher quality is that it can restrict the flow of pico-solar products to narrower distribution channels and limit the opportunities for comparison shopping.

**Improving Retailer Distribution**

Although Kenya has experienced unprecedented success in selling pico-solar products through institutional partnerships, these institutional sales are not considered a long-term solution. Sales through school campaigns can provide an effective stop-gap measure to accelerate the awareness and adoption of solar products in virgin markets, but they do not provide a reliable long-term distribution channel for sustaining sales or after-sales service.\footnote{For example, SunnyMoney has developed a robust distribution network to continue sales after school campaigns. As of July, 2014, SunnyMoney was selling the d.light S2, S20, and S300; the Greenlight Planet SunKing Eco, SunKing Mobile, and SunKing Pro2; the Barefoot Connect 600 solar home system; and the Marathoner Beacon 290 solar home system through its distribution network.} With the greatest variety of products available and opportunities for connecting with customers, retailers figure centrally in strategies for reaching out to customers and communicating information about product quality and performance.

Given that retailers are the primary means by which end-users access lighting products, how does the average retailer decide which products to sell to his or her customers?\footnote{Of all retailers interviewed for this study, 61% were male.} Based on our interviews with retailers, there are at least five factors that figure into the customer's purchasing decision at the retail level: demand, durability, availability, access to finance, and affordability.
Demand and Durability: Sixty-three percent of the retailers that we interviewed learned about new lighting products from their supplier, while twenty-six percent found out from their customers (see Figure 4). In other words, before a retailer can purchase a new product, he or she must first be aware of and sense a demand for the product. But retailers also need information about the product quality, as nearly half of all customers focus on durability as a key characteristic when making purchasing decisions (see Figure 5). Retailers have an incentive to sell higher quality products in order to avoid customer complaints or dissatisfaction, and without other sources of information about product quality they often depend on personal experience, feedback from customers, and assurances from suppliers to decide which products to purchase.

Figure 4: How retailers learn about new lighting products. Retailers could cite more than one source.

Availability: However, awareness and interest are not sufficient: retailers need reliable and consistent access to the product. If the product is delivered, is available from a local sub-distributor, or can be sourced from a trusted trader in Nairobi's wholesale market, then it is much more likely that retailers will be able to maintain consistent stock in their store. If the distributor is hard to find in Nairobi, the cost of shipping is too high, the minimum order for wholesale pricing is too high, deliveries are sporadic or unreliable, or the product selection is limited, then a retailer is less likely to try a new product or technology. From May to June when we were conducting this research, many of our retailers commented extensively on their inability to fulfill consumer demand for d.light products due to the lack of available supply from d.light distributors.

Access to finance and affordability also play important roles in the retailer's purchasing decision. Torches and key chain lights are inexpensive, so it is easy to maintain a steady stock and turn over inventory. Solar lamps are more expensive and sell less quickly, which means that the retailer must either have sufficient working capital to maintain stock or a consistent delivery mechanism for replenishing a small inventory. In some instances, the seller provides informal financing by giving the retailer a three- to fourteen-day grace period before payment is due.
However, affordability is perhaps the most important criteria for retailers and customers (see Figure 5). Low quality products continue to thrive in the off-grid lighting supply chain because they temporarily meet a need at a price that customers can afford. One reason for the success of study lamps, including quality-verified versions, is the fact that they are the least expensive solar lamp available.

In sum, QA information plays a critical role in influencing the flow of products, information, and finance at the top of the supply chain and determining which products are selected by vendors to sell to consumers. Given that vendors can choose between high quality, low quality, and counterfeit products, Lighting Africa has a strong incentive to continue engaging vendors throughout the supply chain to ensure that they are in a position to make informed decisions that ultimately benefit their businesses, their customers, and rest of the market.

Reducing Uncertainty through Indirect Signals
Once a product makes it to market, buyers still may not know how it will perform or how well it is suited to their needs. Absent this information, there are a variety of indirect signals like product presence, branding, or word-of-mouth referrals that can reduce uncertainty for the buyer and inform his or her purchasing decision.
A DOMINANT PRESENCE

With over one million solar lamps sold in Kenya last year, pico-solar sales now represent a dominant share of the total sales revenue for off-grid lighting. Although the selection of pico-solar products is still growing, 73% of the retailers interviewed in this study were selling a product powered by solar. In fact, of more than five hundred products recorded, 40% were powered by solar, more than any other energy source.

The dramatic growth of the pico-solar market has two important implications. First, the marked increase of solar products in the market means that pico-solar is not only more available, it is more visible. Consumers like to purchase products that are aspirational—products that imply a higher standard of living, upward social mobility, or greater status and prestige—and customers with fewer resources are by no means the exception. Therefore, the fact that solar products are stocked in more retail shops, supermarkets, and electronics stores—particularly stores in urban centers where demand is aggregated and consumers prefer to purchase consumer durables—lends to the credibility of solar technology.

Perhaps more importantly, as more solar products are sold, more customers are able to see firsthand how these products perform in their communities. This form of direct, eye-witness quality assurance cannot be understated because, as we will see, customers are most likely to purchase a product that they have already seen, experienced, or heard-about from a family member, neighbor, or other trusted source. When we asked retailers if the customers who purchased solar lamps came in looking for a specific product, 82% answered in the affirmative, indicating a dramatic increase in demand for solar products. In short, the increased visibility and availability of solar products in Kenya is one of the main means by which consumers are gaining more trust in solar technology more generally and in solar products more specifically.

THE EMERGENCE OF BRAND

One key observation made during the field study was that the d.light S2 has become one of the predominant products in the market. Representing almost a tenth of all products surveyed, the

21 Based on reported pricing and sales volumes, quality-verified products represented roughly 50% of the total sales revenue, while all solar-powered products approximately 80% of the total sales revenue for the retailers interviewed in this study.

22 Other categories noted were: 34% that were powered by dry-cell batteries, 31% with grid-charging capability, and 4% that were dynamo charged. With solar charging, the total numbers add up to more than 100% due to products that were powered by more than one energy source.

23 Karamchandani, et al. (2011) "Is the bottom of the pyramid really for you?" Harvard Business Review.
S2 was the most common product that we encountered. Moreover, d.light was the most common brand that we saw in retail shops, representing 17% of all products. Greenlight Planet solar lamps (3.5%) and Tigerhead torches (3.1%) tied for a distant second. Several retailers indicated that they had begun to stock d.light S2 study lamps in response to customer questions and demands. In fact, two hardware stores that did not sell any other lighting products were selling d.light S2 lamps because customers had requested them.

In addition to the increased visibility and availability of d.light products, there was a broad identification of d.light as "the" solar light. Some retailers reported that customers used "d.light" and "solar" interchangeably, and one retailer said that a customer had asked for a "d.light eco." However, as we dug deeper we realized that, despite the broad awareness of and demand for "d.light," customers and retailers were often referring to the S2 study lamp when they said, "d.light." In other words, while in some instances d.light was conflated with solar, in most instances d.light was most broadly identified with the S2 study lamp.

This conflation of manufacturer and model illustrates that consumer perception of products includes multi-layered information, including official branding, form factor, and the context of availability. This could leave popular products like the S2 vulnerable to imposters that can adopt a subset of these signals. We encountered two striking S2 counterfeits while conducting surveys, and one of them was nearly identical (see Figure 7). Given that retailers and customers depend heavily upon the shape and appearance of the product for identification, it was not surprising that several retailers were selling these products and the d.light S2 interchangeably. In fact, when we returned to Kericho to try and locate several Winning Star samples for testing, almost no one knew what we were talking about when we asked for the Winning Star by name.

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24 The closest runner-ups were the d.light S20 at 4% of all products and the d.light D20g sold by M-KOPA representing 2% of all products.

25 The SunKing Eco is a solar lamp that is manufactured by Greenlight Planet and sells at a price similar to the d.light S2. A customer asking for a "d.light eco" is akin to customers conflating "coke" and "soda" in some regions of the United States.

26 The Winning Star TYN 355-372 had the exact same shape, wire stand, and even packaging as the d.light S2. Externally, the only differences were the brand name, a green (instead of orange) rim around the enclosure, and a polycrystalline solar module. (The original S2 solar module was polycrystalline but has since been replaced with a monocrystalline module.) It was also interesting to note that the Winning Star had a slightly larger battery than the S2.
While the growing demand for the S2 indicates that consumer confidence in solar technologies is increasing, it is not clear whether customers are loyal to the form factor or to the brand. In other words, the prevalence of S2 study lamps may have less to do with the emergence of the d.light brand and more to do with the way that the S2 has been promoted in the region. This may explain why brand ranked lower than durability, brightness, and even run-time when customers were deciding which product to purchase: even though most customers and retailers refer to the S2 as "d.light," they may not think of it as a brand (see Figure 5). Understanding the drivers of d.light's success has important implications for how products are promoted in other virgin markets. In particular, when customers identify the product by form factor instead of by brand, the product is more vulnerable to counterfeiting and the ancillary benefits of brand-building (warranty servicing, product upgrading, after sales service, etc.) are diminished.

**The Power of Referral**

As mentioned earlier, SunnyMoney is selling more solar lamps than any other company in Africa. While an analysis of their sales strategy is beyond the scope of this investigation, it is important to highlight how the SunnyMoney model has contributed to the demand for the S2 study lamp in the Kericho area and the flow of information through the supply chain.27

In partnership with the Kenya Ministry of Education, SunnyMoney sells most of its study lamps through head-teachers in public schools. In rural areas with little previous exposure to solar products, head-teachers are recruited and trained to sell study lamps at their schools and in their communities. The efficacy of this model cannot be understated, as the head-teachers are an ideal medium through which to share information about solar study lamps. In talking with parents, students, savings groups, or church members, head-teachers explain the dangers associated with kerosene lighting, the durability and cost-effectiveness of solar lamps, the benefits of switching, and the utility of the lamp for studying at home. With their education and

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27 Please see "SolarAid: Revolutionizing the way to make energy affordable for everyone" by Howe, et al. (2012), for more information.
training, head-teachers are generally perceived as a trustworthy source for information, and their high-standing in the community also lends to the credibility of what they share. Finally, although head-teachers often receive a small financial incentive for selling lights, they do not depend on the income for their livelihood like local retailers or village-level entrepreneurs.

Given their commitment to children's education and their desire to keep the sale simple, SunnyMoney only promotes one study lamp in each school, and in the areas around Kericho they have almost exclusively promoted the d.light S2. Thus, the previous trends we observed—customers knowing which product they want when they enter the store, the greater availability of and demand for the S2, and the strong product-loyalty to the S2—may be due in large part to the unique sales model employed by SunnyMoney. In a recent survey of fifty-eight SunnyMoney customers, participants knew an average of six people who had solar lights prior to their purchasing one. Eighty-five percent indicated that their purchase was influenced by a recommendation that they received, and 64% of participants stated that the recommendation of the teacher was the most important or main factor in their decision to purchase a solar lamp, more than their children (37%), friends or family (34%), or any other community leader (2%). In this way the success of the SunnyMoney model, which has made the d.light S2 a best-seller, involves a confluence of three critical factors: the recommendation of the teacher, the ability to see and experience the product directly in the community, and the critical mass of sales that animate interest and trust in the product.

Anecdotal evidence from interviews with retailers seems to support this hypothesis. Apparently in areas where SunnyMoney is promoting and selling the SunKing Eco, there are similar trends that are developing with consumer demand and product-loyalty. Also, one sub-distributor indicated that neither the Eco nor the S2 seem to sell very well in areas where there haven't been any school promotions. In this way, indirect signals like product presence, branding, and word-of-mouth referrals can exert a significant influence on consumer behavior, particularly when applied in tandem. While an application of this sales model to other markets is beyond the scope of a QA program, it is worth underscoring how widespread institutional sales have positively impacted the rest of the market through increasing product visibility and consumer awareness. The SunnyMoney model in particular demonstrates how the quality of the signal—it's source, whether it can be readily verified or experienced, and whether it appears to influence others in the community—ultimately determines its efficacy in influencing and informing consumer behavior.

Reducing Uncertainty through Direct Signals
While the indirect signals described above play a significant role in informing and influencing purchasing decisions, there are also direct signals like on-the-box labeling, advertising, and sales
tools that can be used to promote products or facilitate comparison shopping. Thus far, the Lighting Africa QA program has been successful in engaging market stakeholders at the top of the supply chain, and this has had a positive impact on the rest of the market. However, there are still opportunities to engage traders, sub-distributors, retailers, and customers further down the supply chain to increase opportunities for comparison shopping and improve the overall flow of information about product quality and performance.

ON-THE-BOX REPORTING

On-the-box reporting is one of the most direct means of communicating information about product performance. In early 2015, Lighting Global collaborated with manufacturers to finalize reporting requirements for light output and product runtime. While the presentation of these performance characteristics will be left to the discretion of each manufacturer, these performance reporting requirements will play a key role in facilitating comparison shopping between similar products (see Figure 8).

ADVERTISING AND PROMOTION

Lighting Africa has worked hard to promote quality-verified solar products in Kenya through road shows, television advertisements, radio advertisements, and marketing materials like posters and fliers. When we asked retailers what they thought were the most effective ways of promoting solar products, 48% indicated that radio advertisements in the local language would be the most effective, followed by road shows (24%, see Figure 9), television advertisements (18%), and fliers (10%). With greater penetration of radios and televisions into rural markets, it is likely that these mediums will become increasingly popular for promoting solar products.
TOOLS FOR PROMOTING SOLAR
In each of our interviews with retailers who sold solar, we also presented four different promotional tools and asked them which they thought would be most useful for learning more about solar technology, training employees, or selling more solar products to customers. The first was an example of a product specification sheet from the Lighting Global website. The second was a graphic representing a quality seal on the box of a solar product. The third was a printed excerpt from a flip book that describes solar technology with pictures. The fourth was a picture of a YouTube video that we explained would provide an audiovisual description of solar technology.\textsuperscript{28}

As seen in Figure 10 and Figure 11, the specification sheets and flip books were overwhelmingly preferred by retailers, both as tools for internal knowledge building and as a means of selling more solar products to customers. Very few retailers had seen one of the Lighting Global specification sheets before, but most expressed interest in the graphical header that displays the brightness and solar runtime for different settings and product features like mobile charging or additional light points. In one case a retailer reported being able to sell more SunKing Eco study lamps by showing customers that it was brighter and had a longer run-time than a similar lamp.

\textsuperscript{28} Please see the Annexes for examples of each tool.
Of course, while retailers figure prominently because they are closest to end-users, they are ultimately vulnerable to the decisions that are made further up the supply chain by distributors. During this investigation, we also conducted semi-structured interviews with fourteen distributors in Kenya, representing a variety of manufacturers and distribution channel strategies. Since the decisions of distributors affect the rest of the supply chain, we also wanted to ask them their opinions about the tools described above (see Figure 12 and Figure 13). While the distributors represented a smaller sample size, they thought that the specification sheets and educational video would be most useful for training their sales staff, but that the flip book and quality seal would be most useful for selling more products to retailers and sub-distributors.

Figure 10: Retailer's most useful tools for learning about and training employees in solar technology (N=94).

Figure 11: Retailer's most useful tools for selling more solar lamps to customers (N=94).
As previously mentioned, Lighting Africa's quality assurance program has had effective engagement with Kenya's solar distributors, so communication and information from Lighting Africa already played a significant role in the purchasing decisions for most of the distributors that we interviewed. For example, two thirds had used the Lighting Global website to find out information related to product quality and performance, and ten of the fourteen had already seen or used a specification sheet before.\textsuperscript{29} In addition, five of the fourteen indicated that they used direct communication with the Lighting Africa team to access information related to the quality

\textsuperscript{29} Two had used it to compare competitors' products, one had used it to decide whether or not to order a product, and one had used it to convey information to his customers.
or performance of the products that they purchase. Not surprisingly, ten of the fourteen indicated that they felt that it was easy to compare the quality and performance of different lighting products. When asked which mediums are most effective for communicating QA information to buyers, online publishing, on-the-box labeling, and radio advertisements were identified as the most effective mediums (Figure 14).

![Figure 14: Distributor's most effective mediums for communicating information about product quality or performance (N=14).](image)

Finally, Figure 15 displays the information about product quality and performance that was most important to customers, retailers, and distributors. During our interviews with the retailers, we asked what information customers asked about or used when purchasing products. The majority of retailers reported that **price** was the most important consideration for customers (52%), followed by **durability and quality** (47%), **brightness** (37%), and **run-time** (36%). Similarly, we asked distributors for information that vendors asked about or used when purchasing products. In this case the most common concern was whether or not the product had a warranty (71%), followed by price (57%), durability and quality (36%), run-time (36%), and brightness (29%). When we asked the distributors what they considered the most important information about product quality or performance, the majority indicated durability and quality (43%), followed by the price, the warranty, and the run-time (21%). While it is interesting that brand was not mentioned explicitly by the distributors, this is probably due to the fact that most distributors deal exclusively with one manufacturer. It is also worth noting that distributors receive a lot more questions about warranties from retailers than retailers receive from customers. Besides these two anomalies, the responses from the different stakeholders were fairly congruent, with **price**, **durability**, **run-time**, **warranties**, and **brightness** figuring prominently in each stakeholder's purchasing decision.

30 Five indicated that they use feedback from customers, five indicated that they do internal testing, and six indicated that they use the internet to access information related to product quality and performance.
Another important finding from this investigation is that mobile handsets and services were widely utilized throughout the supply chain. As seen in Figure 16, the sophistication of mobile technology increased further up the supply chain, with the vast majority of pico-solar and solar home system (SHS) customers using basic phones, retailers having an even split between basic phones and smart phones, and the majority of distributors using smart phones. The rapid penetration of smart phones and feature phones with social media applications could be particularly useful for increasing connectivity throughout the off-grid lighting supply chain. As seen in Figure 17, both rural customers and retailers are increasingly comfortable with a variety of mobile services like text messaging, mobile money, and social media applications like Facebook and WhatsApp. The rapid rise of mobile coverage, access to mobile devices, and digital literacy in rural areas highlights the important role that information and communication technologies are playing in increasing connectivity, facilitating financing, and channeling information flow in off-grid markets.

For the purposes of this investigation, smart phones were defined as mobile phones with touch screens or QWERTY keyboards and the ability to download and manage different applications; feature or internet phones were defined as mobile phones with access to the internet and fixed applications like Facebook, Twitter, or WhatsApp; basic phones referred to the least expensive phones with no internet access or applications.
Reducing Risk through Quality Signals

While indirect and direct signals can reduce uncertainty for buyers, they are not always reliable indicators of quality. For example, manufacturer advertising can increase consumer awareness and brand recognition, but that doesn't guarantee the product's quality. Similarly, a standardized format for reporting product run-time can improve comparison shopping, but it doesn't indicate how long the product will last. Quality signals like warranties, quality seals, and consumer financing play unique roles in reducing risk for buyers in the off-grid market. As such, their support and implementation merit particular consideration for the Lighting Global QA program.

QUALITY SEALS

The idea of creating a quality seal for products that meet the Lighting Global Quality Standards has been discussed at length within Lighting Global and with Lighting Global stakeholders. Western markets have provided a positive precedent for quality seals in the electronics and
appliance industries, including both business-to-business (B2B) and business-to-customer (B2C) quality labels. Examples of B2B labels include the Underwriters Laboratory (UL) certification, the Conformité Européenne (CE) certification, and the external power supply quality label. Examples of B2C labels include Energy Star labels or the Eurovent Certification (see Figure 18).

Although these quality labels have been highly successful in OECD countries where there are protections against counterfeiting, it is not clear whether a B2B or B2C quality label would be as successful in an off-grid market like Kenya. In addition, effective marketing of a B2C label would require a substantial investment in promotion and advertising and strong partnerships with local regulatory agencies to ensure that practices conform to national regulations. Furthermore, implementing organizations may have to adapt B2C quality labels for local languages, which would be challenging in countries like Kenya where there are over 60 languages. Although a B2B label would still be vulnerable to counterfeiting, it would cost a lot less to promote the label among distributors, investors, and retailers in the supply chain and could have a positive impact on purchasing decisions. The possibility of investing in a B2C label could be contingent on the perceived success of a B2B label, its resilience against counterfeiting, and the availability of funding for marketing.

![Figure 18: Different quality labels. Clockwise from top right: Conformité Européenne (B2B), Underwriters Laboratory (B2B), External power supply (B2B), Eurovent (B2C), Energy Star (B2C).]

WARRANTIES
Currently, products that meet the Lighting Global Quality Standards must offer and present a consumer-facing warranty. Warranties signal quality by providing a guarantee of repair or replacement in the event of malfunction during the warranty period (usually one or two years for pico-solar products). In theory, this guarantee holds manufacturers accountable for faulty products and also protects consumers from cheap products being dumped in the market. In practice, it is not always easy for customers to obtain after-sales service because not all retailers honor warranties, there is often an ill-defined process for assessing manufacturing defects versus customer misuse, and determining the exact warranty period is also difficult.\footnote{Please see "Warranty Practices in Tanzania Retail Markets: Market Intelligence Note 4," for more information.} Overall, we found that only 8\% of retailers offered warranties on all products, 38\% offered warranties on products that had manufacturer warranties, and 54\% of retailers did not honor any warranties. However, given that only 20\% of the products that we encountered in the market had known manufacturer warranties, \textit{it was encouraging to hear that, for 78\% of products with manufacturer warranties, the retailer claimed that their business would honor the warranty.}\footnote{There were sixteen of 130 retailers that indicated that they did not honor any warranties, even though they sold products with manufacturer warranties; those un-serviced products represented 22\% of the products with manufacturer warranties that we saw in the market.}

CONSUMER FINANCING
Similar to warranties, \textit{consumer financing can provide a quality signal for customers because the customer can stop paying if the product breaks or performs poorly during the payment period.} Although this method for signaling quality is more abstract than a warranty or a quality seal, several of the customers that were part of our phone interview sample indicated that they thought a PAYG product would be higher quality than a similar product with an up-front payment. The customers that participated in the four focus groups also indicated that "they would like PAYG...because the customer has surety that it cannot be a fake product." One respondent thought that a PAYG product would be higher quality because the additional PAYG technology (e.g. keeping track of energy captured) indicates that it's an improved product. As this customer put it, "When you pay in cash, you can't know what the quality of the product will be...PAYG wants to help you—it shows some concerns."

PERCEPTIONS OF QUALITY
While customers may initially be wary of new products, brands, or technologies, over time these products, brands, and technologies can prove their durability and utility, thereby reducing uncertainty for customers trying to make informed purchasing decisions. Given the rapid growth of pico-solar products in Kenya's off-grid lighting market, it was not surprising that retailers...
thought that solar products in general were much more durable than grid-charged or dry-cell battery products. When the retailers were asked the expected lifespan of each of the lighting products available in their store, solar products had the longest expected lifespan on average (23 months) compared to grid-charge lanterns (6.2 months) and dry-cell battery torches (4.5 months, see Figure 19).

![Figure 19: Expected lifespan for lighting products by energy source (N=473).](image)

**Conclusions and Opportunities**

There are a variety of ways that information about product quality and performance is accessed and shared in the off-grid lighting supply chain. The flow of information at the regional and global levels of the supply chain in particular plays a key role in determining how products are designed, whether or not they receive financing, how they are regulated or supported by institutional stakeholders, and ultimately whether they are purchased, promoted, and distributed by distributors. Further down the supply chain, there are indirect signals like market presence, brand recognition, and word-of-mouth referrals that can help retailers and customers make informed purchasing decisions when comparison shopping is possible. There are also direct signals like on-the-box reporting, in-store sales tools, and advertising and promotion that simultaneously promote consumer awareness in the market while accelerating pico-solar sales. Finally, there are quality signals like product warranties, quality seals, and consumer financing that reduce risk for buyers by ensuring a minimum level of service life.

As demonstrated by the almost exclusive flow of quality-verified products through proprietary, wholesale distributor, franchise, and NGO distribution channels, Lighting Africa and Lighting Global have been highly successful at engaging market stakeholders further upstream in the off-grid lighting supply chain. With Lighting Africa activities beginning to transition to a second phase in Kenya and beginning to ramp up in other Sub-Saharan African countries, there are several opportunities for the Quality Assurance Program during the next phase of growth in the
off-grid lighting market. This final section addresses the types of content and mediums that Lighting Africa and Lighting Global could employ to improve the flow of quality assurance information throughout the off-grid lighting supply chain.

COMMUNICATING QUALITY THROUGH THE SUPPLY CHAIN
In addition to engagement with key market stakeholders at the top of the supply chain, our team identified a variety of opportunities to improve access to QA information throughout the supply chain. As of 2014, mobile network coverage has increased to almost 96% of the population of Kenya, with 70% SIM penetration\textsuperscript{35} and 11% of the population connected to the internet over 3G. The proliferation of mobile phones and services has contributed to dramatic increases in rural connectivity, digital literacy, and mobile-enabled banking and financing. Rapid penetration of smart phones into rural markets has also increased internet connectivity, enabling a whole host of web-based applications like email, Facebook, Twitter, and WhatsApp. Improved access to information and communication technologies (ICTs) combined with a rapid rise in digital literacy in rural markets has significant implications for Lighting Africa's quality assurance program.

**Opportunity #1:** Use radio advertisements in the local language to promote quality-verified products. Retailers and distributors both indicated that this would be one of the most effective mediums for reaching new customers.

**Opportunity #2:** Create a simplified specification sheet that can be accessed easily on the Lighting Global website for each product and encourage manufacturers and distributors to reference and disseminate the simplified specification sheets when interacting with vendors. Also explore the publication of an illustrated flip book that explains how solar technology works, what the benefits are, how to maintain solar products, and how to service a warranty. These flip books could be shared with distributors to facilitate training and promotion higher up in the supply chain, and they could also be piloted among select retailers to test their impact on sales.

**Opportunity #3:** Make the Lighting Global and Lighting Africa websites compatible with smart phones, starting with the product page. While a broader promotional campaign of the Lighting Global website would be required to substantially increase consumer visits, a mobile-friendly website and specification sheet would be an appropriate complement to verification letters, B2B quality labels, retailer specification sheets, flip books, or B2C quality seals. In a similar vein, Lighting Global could acquire lightingglobal.com and redirect it to lightingglobal.org in order to capture traffic from both domains.

\textsuperscript{35} GSMA Intelligence, 2014. SIM penetration is a measure of the total SIM connections divided by the total population. Since some subscribers may have more than one SIM connection, it is not necessarily an accurate representation of unique mobile connections.
Opportunity #4: Create a Lighting Global or Lighting Africa Facebook page. With 50% of retailers and 30% to 40% of customers using Facebook, a Facebook page could be an easy way to connect with stakeholders throughout the supply chain to provide updates on products, information on best-practices, or potential tips and tools for selling and promoting solar. Similarly, Lighting Global could consider exploring Twitter or WhatsApp as a means of connecting with distributors and retailers or facilitating referrals.

Signaling Quality to Buyers
Once a product is available in the market, there is also a need for quality signals that help inform customer purchasing decisions and facilitate comparison shopping.

Opportunity #5: Work with Lighting Global stakeholders to develop a B2B quality label to facilitate product entry and movement in the market. While customs and inspections vary from country to country, an on-the-box quality label could complement the verification letters that are currently used to demonstrate that a product has met the Lighting Global Quality Standards. In addition, a B2B quality label could be easily promoted among the distributors and sub-distributors already connected with Lighting Africa, potentially saving a lot of time and expense as products are updated or replaced with newer versions.

Opportunity #6: Depending on the success of the B2B quality label, its resilience against counterfeiting, and the availability of funding for marketing, consider promotion of a B2C quality seal for retailers and customers further down the supply chain.

Improving Availability and Choices
Before a product can be sold to a customer, the vendor has to be aware of it, sense a demand for it, have reliable access to it, and be able to purchase sufficient inventory. Since most pico-solar products are competing with fast-moving consumer goods like kerosene, candles, and dry-cell battery torches, solar products will need to emulate the movement of FMCGs through the supply chain as much as possible in order to reliably reach rural customers.

Opportunity #7: Engage with wholesale traders in Nairobi. Based on conversations with Lighting Africa staff, there has already been discussion of performing a road show or consumer awareness campaign on Luthuli Avenue in Nairobi in order to connect with wholesale traders. Increasing the presence of solar products in the Nairobi markets could significantly improve comparison shopping for the retailers who travel from rural areas to purchase their electronic and household wares in the wholesalers markets. This is particularly important for smaller retailers who cannot purchase large orders, pay for shipping, or source solar products from the variety of distributors that are scattered in and around Nairobi. In this way, promoting pico-solar in Nairobi would not only increase the desirability of pico-solar products; it would also increase their accessibility for pico-retailers.
Opportunity #8: Support financing and distribution strategies that enable good-quality pico-solar to compete with FMCG lighting products and increase opportunities for comparison shopping in the supply chain. This can include providing working capital for distributors and sub-distributors that have a hard time maintaining a consistent in-country inventory of products. It can also include facilitating financing for larger companies that have reliable payback rates but need additional capital in order to incorporate or expand PAYG financing.

Opportunity #9: Support strategies for consumer-level financing that help customers get over the initial-cost barrier and signal quality through extended payment periods. This can include researching best practices for PAYG financing, collaborating with micro-finance institutions (MFIs) and savings and credit cooperative organizations (SACCOs) to improve product selection, and exploring a wider array of mobile-enabled repayment methods. This could also include data sharing partnerships with PAYG providers for remote product quality testing, PAYG customer phone surveys, and broader market analysis.

With over seven million quality-verified products sold in Africa as of 2014, the Lighting Global Quality Assurance Program has been able to support and participate in an exciting transition in global energy access for off-grid households. As pico-solar products becoming increasingly familiar, available, and affordable to end-users, the need to safeguard consumer interests with reliable QA information will only increase as the market rapidly and dynamically evolves. While Lighting Global prepares for the next iteration of growth in more mature markets like Kenya, we hope that the lessons learned will facilitate and accelerate the penetration of pico-solar products into new markets.
Chapter 3 References


GSMA Intelligence. (2015) GSMA Intelligence Website.


Annexes

About Lighting Global

Lighting Global is the World Bank Group’s platform to support development of commercial markets for modern energy services for the more than 1.2 billion people in the world without access to electricity. Through Lighting Global, IFC and the World Bank collaborate with the Global Off-Grid Lighting Association (GOGLA), the solar energy services industry and development partners to spur growth of markets for clean, affordable, modern energy services.

The Lighting Global product quality assurance program sets the global standard for quality off-grid solar devices and kits. Under the program, Lighting Global presently lists over fifty quality verified solar products from more than 20 manufacturers. The Lighting Global platform provides support to a broad portfolio of country-based regional market development programs - Lighting Africa, Lighting Asia and Lighting Pacific, which work along the supply chain to reduce market entry barriers and first mover risks in key off-grid solar markets.


About IFC

IFC, a member of the World Bank Group, is the largest global development institution focused exclusively on the private sector. Working with private enterprises in about 100 countries, we use our capital, expertise, and influence to help eliminate extreme poverty and boost shared prosperity. In FY14, we provided more than $22 billion in financing to improve lives in developing countries and tackle the most urgent challenges of development. For more information, visit www.ifc.org.

About World Bank

The World Bank, a member of the World Bank Group, is a vital source of financial and technical assistance to developing countries around the world. Our mission is to fight poverty with passion and professionalism for lasting results and to help people help themselves and their environment by providing resources, sharing knowledge, building capacity and forging partnerships in the public and private sectors. For more information, visit www.worldbank.org.
The following table summarizes the different distribution channels that were observed during our field investigation from May through June of 2014.

Table 2: Distribution channels observed in Kenya's off-grid lighting market.

<table>
<thead>
<tr>
<th>Distribution Channel</th>
<th>Organization Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Institutional Partnership</td>
<td>SunnyMoney / SolarAid and Kenya Public Schools</td>
</tr>
<tr>
<td>Wholesale Distributors and Retailers</td>
<td>Distributors of pico-solar products (Nairobi)</td>
</tr>
<tr>
<td></td>
<td>Retailers (Kericho, Brooke, and Talek)</td>
</tr>
<tr>
<td></td>
<td>Last Mile or VLE Distributors</td>
</tr>
<tr>
<td></td>
<td>Open Air Markets</td>
</tr>
<tr>
<td>Wholesale Traders (Nairobi)</td>
<td>River Road / Luthuli Avenue</td>
</tr>
<tr>
<td></td>
<td>Nyamakima</td>
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<tr>
<td>Proprietary Channels</td>
<td>d.light</td>
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<tr>
<td></td>
<td>SunTransfer (SunTransfer and Niwa)</td>
</tr>
<tr>
<td></td>
<td>Barefoot</td>
</tr>
<tr>
<td>PAYG Companies</td>
<td>M-KOPA (d.light)</td>
</tr>
<tr>
<td></td>
<td>Angaza (GLP)</td>
</tr>
<tr>
<td></td>
<td>diviLite</td>
</tr>
<tr>
<td></td>
<td>Azuri</td>
</tr>
<tr>
<td>Franchise</td>
<td>Total</td>
</tr>
<tr>
<td>NGO Partnerships</td>
<td>SunnyMoney / SolarAid</td>
</tr>
<tr>
<td></td>
<td>Brighterlite (Fosera, Exide, BBoxx)</td>
</tr>
<tr>
<td></td>
<td>One Acre Fund (GLP)</td>
</tr>
<tr>
<td></td>
<td>Ecozoom (GLP)</td>
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<tr>
<td>MFI Partnerships</td>
<td>K-REP (Orb)</td>
</tr>
<tr>
<td></td>
<td>Rafiki</td>
</tr>
<tr>
<td></td>
<td>Faulu (Ecosmart)</td>
</tr>
<tr>
<td></td>
<td>KWFT (Thrive)</td>
</tr>
<tr>
<td></td>
<td>Simba Chai SACCO (Barefoot)</td>
</tr>
</tbody>
</table>
FOUR SALES TOOLS

The following four tools were shared with retailers and distributors to determine which would be most effective for sharing information about solar technology, training employees, or reaching out to customers.

Quality Seal on the Box
Educational Flip Books / Flyers / Calendars

**MAINTENANCE**

- To make the most out of your portable solar product, you need to leave the solar panel in direct sunlight, storing the battery and light safely.
- Moving your solar panel out of shady areas to ensure it gets maximum charge.
- If the solar panel is dirty, wipe it clean with a soft cloth, to ensure it absorbs more energy.

**A BRIGHTER LIFE WITH SOLAR**

- Thanks to portable solar products, you don’t have to be afraid of the dark anymore.
- …you don’t have to struggle to see in the dark because of poor quality lighting.
- …and you can say goodbye to unhealthy flames, so you can focus on what matters most.
Internet Video

- What is solar lighting?
- How to buy it.
- How to use it.
Firefly Mobile
Barefoot Power
Results based on test procedures detailed in
IEC 62257-9-5, ed. 2.0
Verify Online: www.lightingglobal.org/products/bf-fireflymg25
Valid Until: September 30, 2016

Lumens  Solar Run Time
63
High

18
Medium

Meets Lighting Global Minimum Quality Standards

Mobile Charging

Light Point

Warranty Information
A 1-year warranty for replacement of defective parts.

Performance Details

<table>
<thead>
<tr>
<th>Performance Measure</th>
<th>Brightness Setting***</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>High</td>
</tr>
<tr>
<td>Full battery run time* (hours)</td>
<td>3.6</td>
</tr>
<tr>
<td>Run time per day of solar charging* (hours)</td>
<td>3.6</td>
</tr>
<tr>
<td>Total light output (lumens)</td>
<td>63</td>
</tr>
<tr>
<td>Total area with illumination &gt; 50 lux** (m²)</td>
<td>0.17</td>
</tr>
<tr>
<td>Total lighting service (lumen-hours / solar-day)</td>
<td>230</td>
</tr>
</tbody>
</table>

* Run time estimates do not account for mobile phone charging or other auxiliary loads; the run time is defined as the time until the output is 70% of the initial, stabilized output.
** Total area with illumination > 50 lux is determined by the maximum area with adequate illumination at a 0.75 m distance and at the distance from which the product would normally provide task lighting service.
*** Additional brightness settings (not tested): Low

Lighting Details

<table>
<thead>
<tr>
<th>Lamp type</th>
<th>LED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description of light points</td>
<td>Single unit on gooseneck with 10 LEDs</td>
</tr>
</tbody>
</table>
| Colour characteristics | CRI 74
CCT "Cool" (5000-7000 K) |
| Distribution type | Wide |
| Lumen maintenance | 100% of the original output remains after 2,000 hours run time |
DATA, KNOWLEDGE, AND ACTION OFF THE GRID

Our market and institutional analysis highlighted both opportunities and frictions that are present in the evolving information-energy system off the grid. The offer of PAYG financing and (implicitly) better support after the sale can lead to a rapid acceleration in uptake for solar energy systems by end-users, but the cost of financing is often amplified by steep mobile money transfer fees and there are high costs for PAYG businesses to integrate with payment systems. The underlying structure of distribution and retail networks incorporates ICT for visibility and payments, supplying more and better quality goods, but access is not universal and there is a range of capabilities among sellers for linking through ICT platforms.

As ICT is integrated throughout the energy system on and off the grid, the data that are generated present new opportunities for insight and challenges as well around appropriately protecting privacy and regulating firms that control the technology systems that capture personal data. With open access to large-scale decentralized energy data across a range of network scales, it may be possible generate timely strategies for transforming energy technology systems to address greenhouse gas pollution. Public interest uses of data could enable regulatory institutions to better protect and support consumers, enterprising developers of technology and distribution models, and scholars to test theories of socio-technical network dynamics (47) and energy use behavioral patterns (48). In general “Big Data” appears to be a potentially powerful microscope for investigating the society and systems in which it is embedded, but only to the extent it is available and rigorously, carefully analyzed with support of domain expertise (49).

Chapter 4, which follows this section, uses off-grid solar system monitoring data to address fundamental behavioral questions about the users of the systems, where traditionally visibility into day-to-day operation is hidden from view. Using a large sample (n=1,112) of M-KOPA SHS customer data, we uncovered evidence supporting a model of end-user decisions balancing reliability with quantity of energy services in the context of variable solar energy availability. We also identified and showed the implications of the fact that half the users frequently move their solar module, reducing the effective solar resource, often due to theft concerns (as we were told in a survey). The findings can directly inform how enterprise and regulators engage to create the market for off-grid solar in the future, influencing the design of systems, the ex ante predictions of service assigned to technology deployments, and the interpretation of joint quantity-reliability data from off-grid power.

BIG DATA SCIENCE

The much-touted goal of turning “data into knowledge and knowledge into action”\textsuperscript{4d} is a useful framework for identifying some of the challenges to implementing data-enabled interventions in technology markets. Deconstructing the phrase highlights important areas of focus for research and policy that our work contributes to.

\textsuperscript{4d} e.g., see a White House Press Release announcing “Big Data” initiatives here: http://www.whitehouse.gov/sites/default/files/microsites/ostp/Data2Action%20Press%20Release.pdf
First is the unstated assumption about the availability of energy data, where the status quo is to be protected and mined by private sector system owners, operators, developers, and integrators, who may extract different value from the data by keeping it confidential and scarce (e.g., by encouraging repeat customers or improving their competitive position with product design improvements). In outreach with PAYG firms we found hesitancy to share (much less make public) even data that had been made anonymous, including information from remote system monitoring and billing and repayment histories. While some of this concern is related to customer privacy, there are also significant proprietary claims for controlling and deriving value from data that were expressed to us. An ethos of confidentiality and claims to the right for data mining is common (but not universal) in the sector. Many PAYG firms are supported by venture capitalists who have been made wealthy and built careers on the growth of ICT into other sectors, where it is ownership and operation of data facilities that creates value for investors.

Public and private uses of energy systems data are important but in tension. The value from global sharing can only occur if sufficiently high fractions (or good samples) of data are available, but there may be reduced incentive to include data collection components in off-grid energy systems without the incentives related to extracting private value from the data before it is made public. The governance of distributed energy usage data generated by systems that are owned by dispersed global institutions, corporations, and citizens is a critical unresolved legal and political issue. It is the subject of ongoing public utilities commission rules (50), guidelines from the US National Institute of Standards and Technology (51), and attention from researchers and project developers who want to understand and mitigate privacy and security concerns to unlock public goods value.

Given some incomplete access to all the streams of data that could contribute to knowledge about the energy system, a key challenge is identifying algorithms and analysis strategies for those data that are available, but first the data must be “clean”. Energy data are often however quite “messy” and disjointed, and in many most cases only yield knowledge in a probabilistic sense on an individual consumer or facility level depending on the original purpose for collection. This fragmentation in the domain of raw data and interfaces between data structures is endemic to many ICT systems and is closely related to one of the core opportunities we identified for institutional support in the emerging PAYG market: better harmonization of interfaces with back-end mobile payments and decentralized energy system operations (9).

The final step, turning knowledge to action, is often most difficult. As we showed in Chapters 2 and 3, given the structure of networks in the market for off-grid solar it is often difficult and expensive to reach the edge of the system with information or goods (i.e., at the retail or end-user level) and more effective to motivate the action of more central actors. The approach we present in Chapter 4 turns background data into knowledge about how people use energy, and offers ways action could be taken to improve monitoring and support of the PAYG sector by those with power over investment, regulatory, and enterprise decisions.
Chapter 4

Off-grid solar energy services enabled and evaluated through information technology

Authors: Peter Alstone\textsuperscript{1,2}, Arne Jacobson\textsuperscript{4}, and Dan Kammen\textsuperscript{1,2,3}

August 31, 2015

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Abstract

Advances in information and communication technology’s (ICT) leading to increased spatial reach and affordability enable new architectures and frameworks for providing decentralized energy services. ICT enables remote payment, monitoring, evaluation, and support of off-grid solar electricity systems that provide vital human-needs service to people without the advantage of a reliable electricity connection. Our work focuses on the particular instance of a pay-as-you-go (PAYG) solar home systems (SHS) in Kenya: the d.light D20-g product (5 Watt solar panel, battery, lights, radio, and phone charging), distributed through M-KOPA between 11/2013 and 11/2014. We use mixed-methods, combining 1,112 hourly monitoring datasets with satellite solar resource sensing in an analytic framework informed by detailed surveys on utilization for a subset of 135 users, 4 focus groups, and extensive experience in the Kenya market. In aggregate PAYG SHS users behavior is consistent with co-optimization of electricity service quantity and reliability constrained by the available solar electricity resource and architecture of the system. The average user consumes 70\% of the electricity that is technically possible given the maximum solar generation potential, but experiences 90\% better reliability than what is expected if quantity is maximized. The average user has only 5\% of hours with no available electricity. We find energy demand is elastic given the available solar resource and external social factors also play a role in access. Half of users frequently move their solar panels (i.e., bringing them indoors, often to protect against theft) reducing the effective solar resource by 30\%, and eventually leading to 20\% less electricity provided and consumed (~2 Wh/day, enough to power a standard mobile phone). For 3 billion people globally without access to the grid or with unreliable grid connections, balancing quantity, reliability, and cost for energy service in the context of linked natural and social systems is critical knowledge for improving clean energy access strategies.
The ICT systems that support this analysis could (if key privacy and data access barriers are overcome) provide channels for large-scale monitoring and assessment that accelerates access globally.

**Funding**

P.A.’s effort was supported by the EPA STAR graduate fellowship, A.J. by the World Bank Group’s Lighting Global program and the U.S. Department of Energy’s Global LEAP initiative, and overall project was funded by NSF Award SMA-1338539, *Information–Energy Nexus Research Network* (to DMK). We thank the Karsten Family Foundation and the Zaffaroni Family for their support of the Renewable and Appropriate Energy Laboratory.

**Acknowledgements**

We are grateful to a number of organizations and individuals who supported and contributed to this research. We partnered with a several organizations to gather primary data in Kenya, including key support from Angaza Design, divi power, SunnyMoney/SolarAid and M-KOPA. M-KOPA also provided raw data from system monitoring. None of our funders or research partners exercised editorial control over this work, but they were allowed to comment to ensure confidential and proprietary data were not inadvertently released. Our thanks go to D. Gershenson, N. Turman-Bryant, M. Mumbi and D. Mugo for expert assistance in the field. Isha Ray and Catherine Wolfram gave useful advice on information technology and energy systems over the course of numerous conversations. Duncan Callaway aided in targeting and checking the data processing algorithms. Ray’s Place near Kericho and Sitotwo Primary School provided roof space and security for solar radiation data collection, and hospitably hosted our research team. This work benefitted from the generously offered opinions, data, experience, and comments of numerous research participants in Kenya and the global off-grid solar supply chain, and participants in seminars at UC Berkeley and sessions organized by the World Bank Group. P.A. and A.J. are regular contributors to Lighting Global, and retail supply chain portions of the fieldwork were jointly conducted for this work and in support of programmatic data collection and production of market research reports. All errors and omissions are our own.

**Author contributions:**

Peter Alstone conceived of this work, directed the field research, made industrial research partnerships, conceived and conducted the analysis, and drafted the article. Jacobson and Kammen are past and current research advisors and collaborators, provided comments on the study framing and methods, and contributed to authoring the final draft.

**Data Statement**

The microdata from surveys and remote monitoring used in this work are kept confidential in line with human subjects guidelines for protecting individual-level data. One element of our
research delves into the ethics and imperative of data sharing in the context of decentralized energy systems, and in light of data breach concerns expressed by individuals in focus groups we are not seeking permission to publicly release raw system-level microdata until further study leads to better understanding of an acceptable level of de-identification required for public availability given known and unknown threats from release. We emphasize (and demonstrate in the paper) the value of third party access to data for supporting better understanding of off-grid power systems, and hope to work with communities of research, enterprise, governance, and market support to balance that potential value with better-understood risks of disclosure and privacy expectations. The scripts for conducting the analysis (including linking with publicly available secondary datasets) are included and documented in full in the supporting information.

**Ethics Statement**

This work was vetted and approved by the UC Berkeley Institutional Review Board under CPHS protocol number 2013-07-5470. We follow best practices for protecting the subjects’ data and inadvertent identification and/or release.
INTRODUCTION
Achieving a transition to a clean energy economy that contributes to that stabilizing the climate (1–3) and equitably provides service (4–6) to a growing global population approaching 9-12 billion people (7) is now seen a grand challenge facing human society in the first third of the 21st Century. Meeting this challenge will require a multi-faceted approach, but general agreement exists that key elements include efforts to rapidly expand electricity access and accelerate deployment of renewable power on a large scale on and off power grids. Complementary to the imperative for rapidly expanding low-carbon electricity generation like solar photovoltaic (PV) and wind power, there is a critical need for deploying the next-generation decentralized and demand-side systems as well: super-efficient appliances (8), electrified heating and transportation (9), and off-grid power systems to reach people beyond the margins of the grid (10). Meanwhile, the past decade has seen rapid shifts in access to information and communication technology (ICT) that is vital for coordinating decentralized energy systems. There are ongoing trends for power-law improvement in the performance and efficiency of computing systems (11). Across many developing and industrialized regions network connectivity is growing to ubiquity, resulting in rapid expansion of digital access and capabilities (12) for individuals, organizations, and institutions.

In the developing world, pay-as-you-go (PAYG) solar home electricity systems (SHS) have emerged as a key instance of these co-evolving trends at the nexus of energy and information (13–15). Access to electricity through SHS meets critical human needs for lighting and communication (16) and eliminates many harms suffered through inferior fuel-based lighting, expensive batteries, and recharging fees, including outsized harms to the global climate (17, 18), public health (19, 20), personal safety (21), and high levels of economic hardship (6, 22). PAYG at its core is digital financing that combines a payment (often through mobile money) with ICT-based payment verification (e.g. with GSM mobile data chipsets embedded in devices or cryptographically verified keypad code entry). PAYG systems harness recent trends in ICT for the developing world: access to mobile phone networks for the majority of the rural poor and increasing use of mobile money transactions (23). The retail business models being pilot tested and scaled up include both micro-loan and ongoing payment for energy service companies. Early indications show PAYG significantly accelerates the adoption of market-based solar energy systems by addressing a number of key barriers: offering end-user financing that reduces prohibitively-high cash requirements for sales of SHS, building trust through sharing risk between the distributor and retail buyer over the payment period, and supporting retail service supply chains. (13) Understanding and supporting PAYG solar is a critical opportunity for speeding elimination of fuel-based lighting and large potential improvements in service levels at the same cost to the user, with the potential to provide foundational energy access to 1.5 billion people.

Against the background of rapidly changing technology systems for decentralized energy and information, this paper approaches a set of newly addressable technical and behavioral questions. With mixed methods that incorporate large-scale system monitoring data and primary social and
market research on the supply chain and end-users, we demonstrate potential improvements on
the status quo in understanding, deploying, and regulating decentralized energy systems. We find
the de facto standard ex ante modeling and market monitoring approaches for SHS can be
improved and augmented with newly-available remote monitoring data, and using individual-
level observations uncover relationships between natural variation and user behavior in
mediating energy service. Our results could inform the design of organizations and programs to
support accelerated energy access.

**Human Development and Solar Electrification**
In parallel with continuing efforts to expand access to centralized grids (and modernize the grid),
there are new energy system architectures enabled with a mix of inexpensive, high-performance,
and good quality basic technology components that scale down well. These comprise a
continuum of service ranging from watt-scale devices that provide basic lighting and mobile
phone charging to kilowatt-scale mini-grids providing service on par with grid electricity (6).
Electrification of communities in the developing world that currently use fuel-based lighting and
other inferior replacement technology (among other energy access strategies) is critically
important for addressing the twin challenges of universal access and climate change, and
decentralized solar systems have the potential to rapidly accelerate progress. Electrification
addresses inequality in service (fuel-based lighting provides 10x less lighting service than
electricity) and outsized emissions from household combustion of kerosene for light (in the case
of open wick flames, resulting in 10x the emissions when black carbon is accounted for
compared to people with electricity). (17, 18)

The opportunity of off-grid solar derives in part from technology advances. Solar PV modules
(particularly crystalline Si), advanced lithium battery chemistries (particularly LiFePO₄) and
super-efficient LED lighting are now used in wide range of configurations: sub-watt, integrated
solar-battery-LED units like the d.light S2 (pictured in Figure 1); ~10 W solar home systems that
power several lights, mobile phones, and basic ICT devices; kilowatt scale solar for community
buildings and mini-grids. (6, 24) The cost of providing service has dramatically fallen as the
price-performance ratios improve for components of the energy system. A recent study on the
cost of off-grid electricity (24) found that since 2009, the cost of providing off-grid electricity
with solar PV and battery storage has fallen by 20% for pico-scale (0-10 W) systems and 40% for
household SHS. Furthermore, with superefficient appliances (LED lighting, efficient
televisions, fans, and radios) the cost of providing service has fallen by another 40% across the
range of solar electricity systems. Overall a 60-70% drop in the cost of service is possible over
just five years of advances, with continued progress expected in end-use efficiency and supply /
storage performance.
ICT ADVANCES

Mobile phones are a critical load for off-grid solar, and are owned or accessible to growing majorities of people in many developing countries (like Kenya). For many, having the ability to recharge mobile phones is of equal or greater importance as modern lighting, since mobile phones enable access to information and facilitate social connections that are highly valued. Mobile phones are critical for connecting people to markets and supply chains, including those in the off-grid solar distribution network (25, 26).

A face-to-face survey across 7 countries in Sub-Saharan Africa (including Kenya) during the same period as our work (April-June 2014) by the Pew Research Center showed that 82% of adult Kenyans who were surveyed own a mobile phone, and half those who do not own one can access one, representing ten-fold growth in access over 12 years compared to 9% in 2002. The capabilities of devices are expanding as well, with a growing number of people using phones with cameras (over half) or smart phones (15%). A majority of Kenyans (~60%) and large fractions of Ugandan and Tanzanian (~40%) people use mobile money (27). Over the same period, significant improvements have been made across the developing world in large communications infrastructure, from fiber undersea cables to widely dispersed mobile phone towers, providing connectivity globally to the village level. Approximately 80% of people in Sub-Saharan Africa (and 60% of off-grid households) are within reach of GSM networks circa 2015 (23).

PAYG SOLAR CONNECTIVITY

There is a broad diversity in technology platforms and business models being tested and deployed with PAYG solar, mixing a range of payment methods, agent and distribution network structures, and connectivity capabilities (13).

Many PAYG systems have onboard GSM machine-to-machine (M2M) data transfer capabilities that enable remote transfer of data and control of the PAYG system, providing unprecedented opportunities to study the dynamics of user behavior in energy systems. Previously, while remote monitoring was possible with costly additional equipment, it was rarely conducted in rural energy access contexts. When monitoring did take place, it typically involved small sample size studies with limited durations. Moreover, efforts took place within a particular research project, e.g., 15 systems monitored for 6 months in Kenya, 2003-2004 (15), or 3 systems monitored for 6 months in Zambia, circa 2000-2002 (28). These studies identified early trends in electricity stacking (lights, radio, television) but were conducted in effectively the pre-internet era in the developing world (few mobile phones and only emerging connectivity).

In contrast, for example, every solar home system sold by M-KOPA through their PAYG business model (over 150,000 in Kenya and expanding in other countries) and other similar systems includes remote monitoring and connectivity capabilities that are used to capture data continuously from the time the devices are purchased until end-of-use, and the users all (by
definition due to the business model) own or have access to a mobile phone from which they can make mobile payments for service.

This represents an orders of magnitude shift from the previous state of visibility into the use and users of off-grid energy systems. The data that are generated by PAYG technology systems are varied, and identification of the value that could be captured is an open question. There are two core sources of data that are captured by PAYG operators: customer repayment data and system remote monitoring. The developers and implementers we heard from indicate a range of uses have been proposed for these, including developing credit histories for customers, remotely monitoring systems for predictive maintenance, and informing product development.

**ANALYTICAL FRAMEWORK**

Our framework for analysis focuses on key areas of understanding for the evolving decentralized energy sector that could be better-informed with large scale remote data: the interplay between system architecture and eventual energy service, supporting and measuring reliability, techno-economic modeling frameworks in support of policymaking, and the behavior of users in response to natural and social factors.

**Evolving Decentralized Energy System Architecture**

Traditional design practices for off-grid solar systems were developed in a context characterized by expensive PV modules (colloquially, “solar panels”). The conventional approach typically involved designs that optimized the size of the battery to manage natural variability in available supply (often with locally specific estimates of resource), with a common heuristic that the battery should provide two (or more) “days of autonomy” for the loads. The implication for these systems, in practice, is that it often takes multiple days to recharge an empty battery because the PV capacity is closely aligned with the daily load.

The systems we observed demonstrate the implications of recent and rapid shifts in the efficiency of end-use technology (superefficiency trends) combined with declining costs for PV and advanced batteries (24), which enables new architectures in power system design with storage built-in to portable ICT and lighting devices and modular sizing. The design of modern off-grid solar electricity systems now often feature much larger solar PV modules compared to the central storage battery capacity and daily loads. The extra power can coincidently recharge devices with on-board batteries (essentially leveraging a distributed system for storage) and “over-sized” solar (in a historical context) provides reliable service across day-to-day and place-to-place variations in solar resource.

Our analysis highlights technology-human systems fundamentals that are at play in supplying reliability along with bulk power for the off-grid power sector. Preconfigured systems are designed to be reliable across a range of solar resource and user management regimes, as opposed to designed for a specific place and user, leading to many cases of “over-sized” PV modules. Rather than viewing this as a shortcoming in the design of systems, another interpretation is that it is appropriate and expected to curtail solar electricity in the context of
inexpensive PV, economies of scale in manufacturing and distributing preconfigured systems, and distributed storage beyond the off-grid power system. Trends in system architecture for pico-PV reflect this least-cost strategy for providing a baseline level of reliable energy day-to-day.

**MONITORING AND MAINTENANCE OF SERVICE**

The current global framework for assessing energy access benefits from technology investments is based on ex ante predictive engineering estimates combined with data from somewhat limited set of field studies (29). As new data becomes available they could be a powerful tool for ex post monitoring to verify and improve the ex ante estimates.

A particularly difficult metric to estimate is system lifetime, which is also critically important for estimating the overall benefit from supporting distribution and use of off-grid power devices. The lifetime depends on a complex combination of factors including technical degradation of electronic components, environmental exposure, user care, and eventual product obsolescence as superior alternatives become available. Remotely monitored systems may provide a reliable signal for tracking the lifetime of systems in the field and responding to failures.

Furthermore, during the operational lifetime the reliability of power is a key element of design for electric power systems of all sizes, from large-scale grids to pico-power systems. To effectively focus effort towards human development with expanded access to electricity it will be important to move beyond measurement of the magnitude of service provided (29) to a focus also on the reliability of the service provided. Ubiquitous connectivity and monitoring could help establish benchmarks for off-grid power reliability and help guide long-range policy along with short-term user support to maintain service levels.

For on-grid power, reliability metrics have been established to track performance of operators and regulation. The widely used metrics are typically coarse (e.g., *system average interruption duration index* (SAIDI), an annual duration of time without electricity per customer), and are meant to facilitate comparisons between electricity systems. Grid power systems range widely in reliability along the SAIDI from less than 10 minutes (Japan), 10’s of minutes (Germany, France), 100’s (USA, Argentina), 1000’s (Indonesia, Brazil, Colombia), and higher (30). For some places it makes more sense to measure in hours rather than minutes, like parts of India (31), Kenya (32), Nigeria (33), and others mostly in the developing world where those with grid access can experience outages totaling 1000’s of hours per year. Outage patterns in particular regions are sometimes widely similar but can also be highly variable on a local scale, where varied investment in distribution systems can lead to disparity in service reliability.

Our work shows how ubiquitous monitoring data can provide a pulse for off-grid power lifetime and reliability. We did not observe significant attrition over the limited temporal extent of the data (from six months to one year of monitoring depending on the date of purchase), but show how high-level metrics like the fraction of systems providing energy service at night (about 75%
in the sample we assessed) could be a useful indicator for fleet-level utilization and lifetime. We also identified an analog to SAIDI for off-grid power, tracking hours when power was not available due to an empty battery and no available solar generation. The average individual system was in a no-power state 3% of the time, or, 290 hours without power over the course of a year. There is significant variability in outcomes from user to user along this metric due to variation in practice, with a coefficient of variation of 1.3, from less than 10 hours per year without power to 1000’s.

TECHNO-ECONOMIC MODELS

The current state-of-practice at the global level for estimating the service provided by decentralized energy systems during their active use is based on the technical capabilities of systems and expressed in terms of the service that is expected. As an example, the model presented below in equation 1 estimates the daily quantity of electricity provided to users of off-grid solar systems based on the basic parameters of the system. The model starts with the peak solar electricity generating potential given the available resource and downgrades that peak theoretical potential based on a set of system-level efficiency components. These include losses from operating away from the peak laboratory-conditions power point of the PV module, electrical losses, and others. This total electricity quantity is translated to service through lighting and other appliances, with service levels depending on the utilization mix and efficiency.

Equation 1

\[
E_{\text{tot}} = G_{\text{sol}} \times P_{\text{PV}} \times \eta_{\text{sys}}
\]

and

\[
\eta_{\text{sys}} = \eta_{\text{mpp}} \times \eta_{\text{elec}} \times \eta_{\text{batt}} \times \eta_{\text{user}} + \epsilon
\]

where:

- \( E_{\text{tot}} \) = daily electricity used (Wh)
- \( G_{\text{sol}} \) = daily solar resource (kWh m\(^{-2}\) d\(^{-1}\))
- \( P_{\text{PV}} \) = PV module peak power at standard test conditions (W @ 25°C and 1,000 W/m\(^{2}\))

and

- \( \eta_{\text{sys}} \) = the overall efficiency of the system (%)

which is comprised of:

- \( \eta_{\text{mpp}} \) = fraction of power available after correction for operating away from standard, peak power, due to temperature and voltage matching effects.
- \( \eta_{\text{elec}} \) = fraction of power available after correction for losses in electrical circuits and power converters.
- \( \eta_{\text{batt}} \) = fraction of power available after charge/discharge cycle in battery
- \( \eta_{\text{user}} \) = fraction of power available and used given the variance in user practice
- \( \epsilon \) = error from missing terms that could improve precision of the model

Use-phase service estimates based on versions of the model with varied assumptions are used directly for supporting and tracking markets. In global-scale use cases with little information
about user behavior or context (e.g., global product quality verification (34) and emissions reduction certification (35)), simplifying assumptions are made to estimate the total service provided. These often include using a a “standard” solar day of 5 kWh/m²/day (24, 34), assumptions that the PV module is exposed to 100% of the available solar resource, and of user behavior that leads to maximizing the use of electricity, or that there is a standard use-profile for appliances that applies.

With trusted performance data on which to base estimates (e.g., third party quality verification (36)), this practice of using standard models makes it possible to compare household energy systems along technical dimensions. However, this method also lacks fidelity for targeting local or user-specific needs and conditions and does not offer a good mechanism for ex-post estimation of the service provided by systems in the field.

To identify potential improvements on the status quo, we used remote monitoring data to estimate the quantity and reliability of electricity provided by off-grid SHS. In summary, we found that users manage their loads to use more electricity during times of surplus (an elasticity in demand) but only rarely (~10% of days) completely use the available energy, often “losing” half or more of the potential solar electricity generation because the battery fills before the end of the day and solar charging is curtailed. The end users in our study used about 70% as much electricity as the expected amount available, indicating that they did not manage their loads in a way that maximized overall electricity consumption. However, their systems provided them with higher effective reliability in terms of day-to-day electricity availability because their batteries were generally fully charged even on days that had low levels of solar resource availability.

**User Behavior Estimation**

Directly measuring the dynamics of user behavior that underlie energy access through off-grid power systems has traditionally been difficult and expensive, leading to relatively little understanding of how users manage appliances on the demand side, and sometimes actively manage generation on the supply side. User surveys, interviews, and focus groups have long been used for estimating these dynamics (augmented with limited household monitoring). These approaches continue to be the main methods for obtaining nuanced feedback from users. Findings from utilization of these methods can be benchmarked using national-level household surveys like the census data, multilateral organization surveys, and household expenditures to estimate broader trends, but this approach does not provide information about the day-to-day diversity in service levels and use patterns. With a foundation of telephone surveys, focus groups, and market observation to contextualize and guide our approach, we show how remote monitoring can break new ground in social-behavioral estimation by digging deeper on a long-standing supply-side behavioral question: What is the effect on service when users actively manage not only the loads but also the solar generation by moving the module from place to place?

The placement of solar modules and frequency of moving them directly influences the amount solar energy that is incident on the solar module, and this is a key variable that helps determine
the amount of energy service that can be provided using off-grid PV systems. There are a variety of reasons that solar modules might be moved from place to place. Some systems (like the d.light S2 product pictured in Figure 1) are fully integrated, so the device as a whole, including the solar module, must be moved between charging and use locations on an hour-to-hour timescale. Others pictured in the figure have a separate solar module connected by a cable to the battery and/or loads that can optionally be moved place-to-place or permanently mounted. Past studies and evidence gathered through our surveys indicate users move these separate modules (and craft their charging strategy with integrated systems) in response to concerns about theft (37, 38), weather and its (perceived) potential to damage the product, desire to optimize capture of energy, and other factors.

Our work estimates the effective solar resource that is available day-to-day in the context of variable management practice on both the supply and demand side. We find half the users frequently move their solar module, leading to a 30% reduction in the effective solar resource available based on the timing of exposure to outdoor conditions. When the variation in available solar energy is mediated through variation in demand-side behavior, we estimates that those who frequently move their module are able to use 20% less electricity, while being subject to additional non-monetary costs to operate the system from the effort spent on day-to-day management.

EXTENDING AND ACCELERATING ACCESS
Organizations that engage with the emerging off-grid power market have rapidly shifting access to information and data from the field to improve their approach. Particularly at the global financial and policymaking level but also at the regional and local distribution level, conventional estimates for technical and end-use dynamics lean on sparsely available and highly valued survey-based models and intermittent or second-order monitoring. A key challenge to improvements is that the visibility for particular devices often ends at the boundaries of organizations that transfer products down the supply chain, particularly at the sub-retail level where products are eventually used. Early product failure manifests as dispersed warranty claims, and scarcity or surplus in energy service manifests as word-of-mouth feedback and sales volumes. The techniques we demonstrate offer new insight and methods for understanding the diversity in user preferences for off-grid power, the implications of user behavior for overcoming challenges to energy access, and ways that remote monitoring can improve on legacy methods for tracking and supporting decentralized technology networks.

Through our analytic framework, we demonstrate the capabilities of combined information-energy technology systems for better understanding energy access, but we also bound the potential of these new approaches by considering important issues related to end-user agency and privacy in cases where personal data are used for large-scale analytics. The interests of end-users and organizations that have access data generated by the decentralized energy systems are sometimes – but not always – aligned. End-users in our focus groups expressed an understanding
of the benefits of sharing data about their system and use patterns, but they also expressed measured concern about the potential for harm from data breaches or misuse. These social-behavioral-technical dynamics of large technical potentials and emerging social norms around ICT are aligned with grid-based electricity users who are also being asked to share data and engage with demand-side energy systems to support the dramatic shifts towards renewable power supply required to address climate change (39–42).

Figure 1: Views of off-grid solar products deployed for charging in rural Ethiopia, in March 2015. The top panel shows ~10W household solar systems permanently mounted on the peaks of metal roofs. The lower-left shows a ~1W system with an external module, with the module placed on a ledge next to a west-facing door (and shaded from the mid-day sun in this photo). The lower-right shows a sub-watt integrated solar device, the d.light S2, hanging on the wall of a kiosk in a market center. (all photos © 2015 Peter Alstone)
MATERIALS AND METHODS
This study uses mixed methods to investigate the dynamics of day-to-day energy service from off-grid solar. We combine quantitative and qualitative synthesis to provide insight on the relationship between user behavior and natural variation in energy resources. The analytical techniques described below were used and/or developed to support this work.

STUDY SCOPE AND PRIMARY DATA COLLECTION
This work is based on detailed engagement in the Kenya PAYG market during calendar year 2014, where our team conducted both broad research on the market dynamics for off-grid power and focused engagement with two companies that utilize PAYG business models: M-KOPA and SunnyMoney (more details in the supporting material). We worked to gather social data across the supply chain through surveys, structured interviews, and focus groups. These are combined with a set of remote electrical performance monitoring data (voltages and currents) from M-KOPA PAYG systems and other supporting datasets as inputs for the analysis. The PAYG system data are from n=1,507 selected solar home systems that were distributed in Kenya over the year previous to June 2014 (see Supplementary Materials for details on sampling). Of those, 160 users completed in an in-depth telephone survey about their use and payment patterns for the system. The broader goals and data collected in that work is detailed in the supplementary material.

SURVEY AND FIELD DATA EXPLORATION AND INTERPRETATION
The telephone survey data (n=205: 160 of whom were M-KOPA customers and 45 of whom were SunnyMoney customers), market survey data (n~150 retail and distribution agents in Kenya), and focus group outcomes (n=4 groups @ ~10 persons/group of SunnyMoney PAYG customers) are a main source of qualitative insight to inform the structure of the quantitative analysis of system data and support the interpretation of the results. A synthesis of the results that inform our approach is included below. We have reported on other aspects of these results in other reports that derive from the broader research effort (13).

OFF-GRID SOLAR USERS
The users of off-grid solar who participated in our survey reported a wide range of demographic profiles and energy system management practices. Many of them get their primary income from farming (~50%), while others run a business (20%), earn income as teachers (7%), or engage in a range of other occupations including religious ministry, street hawking, fishing, and others. Before purchasing and using their solar home systems, the users relied on a mix of incumbent energy systems that are typical for those without access to electricity. Many used more than one type of incumbent technology, with median reported spending of $1.60 USD per week on
lighting, $0.23/week on mobile phone recharging (80% of people pay fees to recharge their phones, traveling a median distance of 1 km for the service), and $0.45 on dry cell batteries for radios for a total of $2.30 in expenditures plus a number of hours and kilometers traveling to access fuel, charging services, and/or dry cell batteries. This corresponds to a median 12% of income for status quo energy spending, which is somewhat higher than the typical fraction among off-grid people in Kenya but within the range of expected values, particularly for lower income people who tend to spend a relatively large fraction of their income on energy (6, 22). Hurricane lamps are the most common lighting technology (used in 60% of homes), followed by less expensive and lower quality open wick lamps (40%). Eliminating the use of kerosene lamps is a critical public health issue (21), and the black carbon emissions from open wick lamps in particular are substantial (17), presenting a clear opportunity for climate mitigation and development (6).

Ten percent of users already had another solar lamp or power system in the household and were adding to or replacing it with the M-KOPA system, reflecting the rapid growth in the Kenya solar market and demonstrating an energy stacking effect for off-grid power: beginning with a (typically) smaller and lower-power system and adding another technology system to add functionality and/or improve quantities of service (43).

Energy stacking at the margins of the grid also includes adding reliability of service. Among the incumbent lighting systems there were also notably 10% of users who already had a grid connection, which presumably was not reliable or good enough quality to preclude purchasing off-grid solar as a backup (or primary power system for lighting, phone charging, and radio). These ostensibly grid-connected users report indicators of higher affluence (but not significantly) than those without grid access (mean of 2% higher income, 6 months earlier adoption of mobile money over a multi-year period, and 10% higher spending on mobile phone credit). There are varied technology adoption strategies for users stacking electricity service at the margins of the grid across dimensions of quality, quantity, variety, and reliability of energy service.

**USER MANAGEMENT OF LOADS**

Once the solar energy systems are in use, people report a variety of use patterns. Understanding the actual profiles of use for off-grid energy systems is important for improving system design and understanding the dynamics of energy access outcomes.

For the lights and radio included with the system, the use ranges from 1 to 12 hours a day. Figure 2a shows the distribution, with median reported use for lighting at 4 hours per day for the two “main” lights and three hours per day for the secondary, portable light, which is in line with the other reported hours of use for fuel-based lighting users. People report recharging 2 or 3 phones a day, typically, and some individuals recharging up to 5 or more phones. Keeping phones charged is not only a key value for users but an enabling factor for making payments and
accessing the energy system, since mobile money use is a necessary information technology application for keeping up with payments.

The off-grid solar users in our survey mostly use standard model phones have limited features beyond voice, text, mobile money, and account management (“feature” phones in the parlance of the mobile handset industry), but many (42%) also use “internet” phones with a wider set of predefined internet-based features (e.g., facebook and email) and some (11%) use fully internet-enabled “smart” phones. The profile in ICT access among the users skews towards a higher level of access than the broader off-grid population in Kenya, perhaps reflecting a degree of digital savvy (or wealth, which is difficult to disentangle) among those who opt-in for a digitally financed energy system. As users add devices and upgrade from normal phones to more energy-intensive internet-enabled and broadband handsets, the energy demand on the system will increase to meet the growing household ICT load.

Combining the survey results with remote monitoring data allows us to benchmark user-reported hours of use to what is observed on a day-to-day basis. Figure 2b shows that the mean observed hours of use at night for remotely monitored systems has a similar distribution and median to self-reported recall surveys, but on a person-to-person basis the reliability of recall has relatively poor predictive power, with a coefficient of determination for a linear model only 0.13 (Adj. R², see regression plot in Supporting Material). The implications of our comparison between surveys and the remote monitoring data are two-fold: they support the idea that surveys can establish good group-level and aggregate service levels (i.e., the “wisdom of the crowd”), but they also highlight potential for inaccuracy when applying regression and classification models that rely solely on recall survey data (i.e. surveys that ask respondents to report on past activities).
Figure 2: (A) Hours of lighting and radio use reported for a typical day from survey participants (n = 135). (B) Mean daily hours of use during periods when the sun is down (after sunset and before sunrise, in the morning). (C) The relationship between the number of hours a day solar modules are illuminated in the sun and the eventual estimated use of electricity. (D) The daily solar resources and the eventual estimated use of electricity. The points in the upper plots of C and D are aggregated at the system level (the mean over the period of use), and the kernel density plots in the lower sections of C and D show the variation in those means for the ordinate axis.
USER MANAGEMENT OF SOLAR MODULES

For grid-connected energy analysis, this is where the influence of day-to-day user-behavior typically stops: with the operation of appliances and other loads. In the off-grid pico-solar context, however, the user also has influence over the supply side, namely, in management of the solar module. Among those in the survey, 40% report that they actively manage the solar module (i.e., that they move it around), with the vast majority (86%) of those reporting moving it every day, and essentially the rest (9%) every 2-3 days. This active management typically (in 90% of cases) involves moving the solar module indoors for periods of time, and the overwhelming reason for this active management is that users are afraid of theft, with 80% of users who move the module citing security concerns. Other reasons users cite (a small minority of cases) included an intention to permanently mount the module in the future, difficulties mounting due to issues with their roof, and in one case, the enjoyment of moving the module around. With many users moving their solar module in and out of doors, there are obvious implications for the effective solar resource exposure if the module is left indoors or under shade cover for part of the daytime.

A coarse analysis of the remote monitoring data (Figure 2c/d) shows that the number of hours a solar module is illuminated matters for determining the eventual quantity of available electricity that is used at night, with relatively low dependence above 7 hours per day, but clear reductions in service for shorter durations. As a point of comparison, Figure 2d shows the weaker relationship of energy service and the average solar resource, suggesting user management (changing the number of hours that the module is in the sun) plays a stronger role in determining the amount of solar energy that is captured than regional geographic variability in the solar resource over distances on the order of 100’s of km (including an area that ranges from coastal lowlands to mountainous regions).

SPATIAL LOCATION ESTIMATES FOR OFF-GRID SOLAR SYSTEMS

The location of devices is important for estimating the available solar resource, but for solar home systems sold through retail channels these are often unknown beyond the final point of sale without supporting data. Exact (GPS based) estimates are not available in our data, and the approach we take for estimates is using the known locations of mobile telecommunications towers that are used for system data transfer. These towers have a limited and heterogeneous spatial reach. The common rule of practice is to assume that connections to mobile towers can occur within 10 km (the approximate reach of towers), but in the dataset we observe that the sequence of towers used for day-to-day communication often fluctuates widely in space, utilizing towers that are separated on the order of 100 km. The transmission power and antennae sensitivity of mobile phone towers are variable, and it appears, based on the data, that in machine-to-machine (M2M) applications the reach of some towers is substantially farther than the conventional expectation for voice calls. To account for the fact that some towers have significantly higher “catchment areas” for systems and others are weaker, we use an “inverse power rated triangulation” method for estimating the location of solar home systems in space based on the towers used for communication. The three-step process to estimate the location is
described here conceptually and implemented in R code notebooks that are available in supporting information: 1) Align the tower location data with rasterized population density estimates for Kenya (based on 1999 census estimates of population density from the World Resources Institute). 2) Find the number of times each tower was used for a communications event by all the systems (the systems “call home” about once a day). The number of instances is a proxy for the power and sensitivity of the tower. Correct these for population density by dividing by the population that lives within a 10 km buffer radius to estimate a normalized power metric for each tower. 3) For each system, estimate the location by finding a spatial average latitude and longitude of all the mobile phone towers that are used, weighting by the number of times each tower is used to communicate with the system divided by the normalized power metric. This will tend to estimate that systems are closer to towers that are used more often by that system but will reduce the influence of “high reach” towers compared to local towers.

**Solar Resources Estimates**

Based on the locations for the systems, we use data from a satellite project to estimate the daily mean solar radiation at the site of each device. The satellite data are an operational Shortwave Incoming Solar (SIS) product from the Satellite Application Facility on Climate Monitoring (CM SAF) (44). Independent researchers have verified the satellite estimates compared to reference measurements of global horizontal irradiance from ground-based monitoring and found reasonable variation within the limits of certainty for the ground-based pyranometers (45). We downloaded the data from the CM SAF website user interface. The data were projected into the same coordinate reference system (WGS 84) that we used for the system location estimates using the bilinear interpolation algorithms (remapbil command) from climate data operators (CDO), a standard library for manipulating climate data. The CM SAF SIS data have a resolution of 15 km square grid cells (and we re-project to a 0.1° grid with 11 km resolution near the equator), which is on the same order of magnitude in precision as our location estimates based on mobile phone towers. Figure 3 below shows the result of analysis steps 2 and 3. The map in panel 3a shows the estimated location for each of the systems in our dataset with the mean solar radiation over the period of record (2013 through 2014). These locations estimates are based on an algorithm described earlier and shown graphically in panel 3b. Some notable features of the sample are the clustering of systems in western Kenya, where a large portion of the off-grid population lives (3b) and there is heavy density of cropland (3c-d). There are far fewer systems in northern areas of the country where there is higher solar resource but poorer farmland and sparse population.

These daily estimates are used in two ways, below. First, they are used to assess the day-to-day and longer timescale (with appropriate statistical transformation) patterns of use and outcomes. Second, in cases where hour-level dynamics are assessed (the M-KOPA SHS data are on an hourly basis) we disaggregate the daily resource available into hourly estimates. These hourly estimates are made using a linear regression model to predict the fraction of the daily total resource in each hour of the day. The model includes fixed-effect terms for each hour of the day.
interacted with the daily total resource. It is trained (i.e., the model was originally fit) with a curated and released dataset of 3 years (2000-2002) of hourly insolation estimated for 32 sites in Kenya (46). The regressors included in the model (hour of the day interacted with daily total insolation) have an adjusted R$^2$ value of 0.85 and were subsequently used over the range of the CM SAF dataset to predict the hourly mean insolation.

We benchmark and verify the overall approach for resource estimates with comparison to fixed pyranometers with 5-minute-scale datalogging that were installed in two locations in western Kenya during a field research mission over the period of ~ 1 month in June 2014. This benchmarking is documented in the supplementary information, and it showed that the overall relationship between the observed and satellite estimated solar radiation is not statistically different from a 1:1 relationship, with no significant differences in the trend between the two locations where we monitored. On a day-to-day basis, where the influence of local topography and microclimate may have larger influence, the adjusted R$^2$ value for the relationship is 0.44. This suggests that long-run aggregate measures of performance based on the satellite monitoring are more valuable than day-to-day point estimates, which nonetheless can be useful.
Figure 3: (A) A representation of the location estimation for a single solar home system. Each crosshair is the location of a mobile phone tower that was used at some point to communicate by the system, and the spatial location estimate is ringed in green. Kenya population density information is in the background and is estimated with 1999 census data by the World Resources Institute (used from the supporting data for their 2007 Atlas of Ecosystems and Human Well-Being(47)). (B) Estimated location of each pico solar-home-system in the remote monitoring dataset (black points), overlaid on a map with the estimated mean daily solar radiation over the period of record (January 2013 – August 2014), with the political boundaries of Kenya demarcated. Note that this set of systems includes a three large, separate samples of the population, one that was randomly selected (n~977), another for randomly contacted survey participants (n~135). The total sample size in B is 1,112. (C) Kenya crop cover density, as identified by a crowd-source remote sensing approach to estimate the cropland cover with 2005 as a base year. (48) The political boundary of Kenya is shown as a black outline. (D) Visible ground cover map of Kenya with key regions / cities noted, from the USGS Landsat archive (49).
SYSTEM OPERATIONAL STATE IDENTIFICATION

Using hourly-scale measures of electrical state from the distributed energy systems, we develop metrics to estimate meaningful information about the use and performance of each system. Our estimates and interpretation of the data are based on the physics of off-grid power systems. The following electrical system data are at the heart of the remote monitoring dataset: battery voltage, battery current, and solar module voltage. Figure 4a shows how the components of the system relate to the data that are gathered. A snapshot of the day-to-day dynamics for an example system is shown in Figure 4b. In the time-series chart a number of important phenomena for this analysis are visible: 1) post-sunset and negative battery current typically indicates the use of loads such as lights or mobile phone charging; 2) pre-sunset negative battery current indicates early morning use of power for lighting and other uses; 3) At night and when the solar module is not illuminated the voltage of the solar module is very low, which could identify active user management of the solar module if it is observed to be “dark” after sunrise or before sunset; 4) When the battery state of charge is 3,000 mAh the battery is full and the solar module is shifted from its normal daytime maximum power voltage to a curtailed open-circuit voltage.

The voltage signal from the solar module helps identify the patterns of management. When the voltage is very low (less than ~5 V) the module is completely shaded (i.e., indoors or covered completely outdoors). When the voltage is high (greater than ~5 V) it signals that the module is illuminated (even by diffuse light). There are two states that represent distinct operating regimes under illuminated conditions: one that is near the maximum power operating point of the module (around 7.5 V) and the other near the open circuit voltage (near 11 V). When the module is near open circuit, it is in an idle state, providing ~0 W. In maximum power mode, the module provides power that is proportional to the available solar resource, limited by the demand for power. Solar modules in maximum power mode are recharging the battery, powering a load, or both simultaneously. The module is put in open circuit mode when the battery is full and there is not another demand for power. Relatively tight clustering of these operational states (shown in Figure 4c) allows a simple one-dimensional classification algorithm based on solar module voltage described in the state definitions below:

State Definitions: Solar module operating voltage – power producing state classification

\[
\begin{align*}
S_{solar}(standby) & : V_{sol} < 1; \\
S_{solar}(maxPower) & : 6 < V_{sol} < 9; \\
S_{solar}(openCircuit) & : 9 \leq V_{sol}
\end{align*}
\]

Where:

- \text{Ssolar(name)} = solar module operating state name
- \text{Vsol} = solar module operating voltage (V)

In the system measurements, the battery current is the sum of the solar generation (positive) and instantaneous end-use load (negative). Because there is only one measurement, it is not possible
to reliably disaggregate generation from load during daytime hours when there can be simultaneous use and generation. We thus treat the battery current in several ways in the analysis: For nighttime hours, the current is known to be “from” the battery, and if it is above a minimum threshold could potentially be powering lamps (and/or recharging devices). During the day, we estimate the available power from the solar module and its control system using knowledge of the PV states described above, namely that when the module is in the maximum power voltage range (approximately 6-9 V) the solar module is actively producing power using the available sunlight. During these times we use standard assumptions about the PV system to estimate the PV power assuming there is no load (e.g. we assume that 80% of the module’s peak power is delivered to the battery for a given available solar resource to account for losses related to deviation from operation at the peak power point, losses related to temperature droop and electrical resistance, and a module peak power rating of 5 W). During many times this will not be true, i.e., when there is power being consumed coincident with solar charging, but it is not possible to derive estimates of when this is occurring without additional information about the load or an isolated measurement of solar current that is not available to us for this analysis.
Figure 4: (A) photograph of the M-KOPA distributed d.light D-20g system plus appliances that were typically included in June 2014, along with a box / line diagram with key components identified. Lights 1 and 2 are hanging, hard-wired fixed-point luminaires that are independently switched (85 lm brightness according to third-party verified test results used to report this and other publicly reported metrics (50)). Light 3 is a rechargeable, portable lamp (25 lm). The peak number of hours a day for a full day of charging is 7 hours (using both main lights at once on the high setting) and longer for the low setting, up to continuous, 24 hour per day lighting. (B) Histogram of PV operating voltage, with notes on a set of operating regimes that depend on the voltage in an illustrative diagram. (C) A plot of the system dynamics as revealed through remote monitoring data. The variables for electrical state include vsol, the solar module voltage (mV); ibat, the battery current (mA); socbat, the battery state of charge (mAh); and vbat, the battery voltage. For reference, the expected times of sunrise and sunset based on the system location are indicated as well using symbols along the abscissa.
We classify the solar management practice of remotely monitored systems using observations of the solar module state near sunrise. Among those who were surveyed and reported active management of their solar module, we observed that there are relatively large day-to-day variations in the duration of time between sunrise (as expected from their location and standard solar geometry calculations) and the first observed time when the solar module is illuminated (i.e., with a voltage in maximum power point or open circuit state). For people who reported permanently mounted solar modules this delay was relatively constant day-to-day. We developed a metric that is described in Equation 2 below. If $D_{typ}$ is less than 1,000 seconds (i.e., typically less than ~15 minutes difference in day-to-day patterns of variation), we classify the system as permanently mounted. Otherwise it is classified as actively managed. The details on this metric are available in the supporting material and the classification is shown in Figure 5a. Among those who were surveyed, the classification approach successfully predicts the self-reported management practice 83% of the time (112 out of 135 responses). Note in Figure 5b that due to inconsistency between user-reported management practice and observed divergence patterns, it is not possible to significantly improve our classification agreement with user-reported practice. We note that during exploratory analysis it was clear that, while many survey respondents provide accurate information, we also observe day-to-day patterns of system observations that are contrary to the stated management practice in some cases (e.g., people who report permanent mounting but whose system has wide swings in time that the solar module is first illuminated from day-to-day that cannot be explained without active management). We posit that some of the false classifications are therefore a result of mis-identification by survey responders who may have misinterpreted the question while others are a result of active management users who may be placing the module outside before sunrise on enough mornings to mis-classify their use as permanent mounting.

**Equation 2:** divergence in sunrise timing metric

$$D_{typ} = median[abs(d_i - \bar{d})]$$

where:

- $D_{typ}$ = the typical absolute divergence from normal day-to-day differences
- $d_i$ = the series of daily lagged differences in the delay between sunrise and first solar illumination.
- $\bar{d}$ = the mean of all $d_i$
Figure 5: (A) Day-to-day lagged differences in the delay between sunrise and the first time when the solar module is illuminated for a set of anonymous survey respondents who self-classified their solar management practice as permanent mounting or frequent moving. These nine systems are chosen to be representative and instructive. The data shown here are the basis for calculating the typical divergence in practice, a metric for classifying practice categories in unknown individuals. (B) Empirical cumulative distribution estimates for the typical divergence (def. Eq. 2) for systems in the dataset. The colors correspond to three independent groups of users: those who self-classify as “Permanently mounted”, those who self-classify as “Moved around”, and those who did not participate in the survey are shown in grey.

**Metrics for System Performance and Energy Service**

Our goal in this culminating element of the analysis is to synthesize performance metrics that describe the level of energy service provided to the user. The ultimate service from household-scale solar energy systems essentially depends on three factors: the possession and timing of use for appliances, the available solar resource, and the effectiveness of capture for that solar
resource, which is subject to significant heterogeneity based on user management practices along with de-rating from shading, dust, or electrical issues.

In the case we are studying, the technical characteristics of the solar home energy systems are essentially uniform (all of the same make and model, the d.light D-20g) and the set of appliances is partly defined by what is included in the package: two fixed point LED lights, one portable LED lantern, and a portable radio. Variation in service demand comes from different utilization of those appliances and user-supplied loads (e.g., mobile phones) that can be recharged with the built-in USB port.

We define the ultimate service to the user with several metrics that describe different elements of service to the user and are observable in the context of the available data:

1) The effective solar resource, combining satellite observations of global radiation with the hour-to-hour observations of systems to reach an estimate of the maximum fraction of solar energy that is available.

2) The number of watt-hours of energy available during times when the solar module is producing power, leading to an estimate of the total watt-hours generated. This is a proxy for a missing measurement in the dataset we analyzed: the measured power of the solar module. We impute this value using methods described in supporting material. The basic temporal unit of analysis for daily estimates (in this and other cases) is a day combined with the whole following night, until the next sunrise.

3) The energy used at night, based on the daily energy swing of the battery \( E_{\text{swing}} \), defined as the maximum minus the minimum state of charge of the battery over the course of a day-night cycle \( [\text{SOC}_{\text{max,d}} - \text{SOC}_{\text{min,d}}] \). This is relevant because can be used to estimate the number of watt-hours a user has used at night (or during daytime periods of scarcity) for powering lights and other loads. We take the difference between this estimate and the previous estimate for solar energy generation to find the estimated direct use of energy during the day, when power is directly delivered to mobile phone chargers, radios, and other devices.

4) A set of user experience metrics that relate to reliability:
   a. The number of hours when electricity is used at night or early morning hours, indicating the potential to power modern lighting to offset kerosene, a key public health and utility goal, similar to the SAIDI metric used for measuring grid reliability.
   b. The annual number of hours when electricity use is limited by deep discharge protection, indicating the likelihood of users experiencing a condition where power is unavailable. This is defined as any hour when the battery state of charge is \( \leq 2\% \) above the minimum level. This off-grid SAIDI metric corresponds roughly (but not exactly) to SAIDI metrics that are applied to grid-based reliability. Those typically include correction for weather extremes (the driver for grid-based outage, typically).
c. We also estimated the expected off-grid SAIDI using an energy quantity maximizing behavioral model as a point of comparison for the observed SAIDI. It is defined in equation 4 below. The daily results are aggregated into a system-level mean over the period of operation for each system.

**Equation 3:** Expected off-grid SAIDI model based on maximizing quantity of electricity consumed at typical use rates:

\[
t_{\text{outage}} = 24 - t_{\text{sun}} - \{E_{\text{peak}} \cdot \bar{w}_{\text{night}} / \bar{P}_{\text{load}}\}
\]

where:

- \(t_{\text{outage}}\) = daily hours without power
- \(t_{\text{sun}}\) = daily hours with sunshine
- \(E_{\text{peak}}\) = peak daily energy generation given standard model (Wh)
- \(\bar{w}_{\text{night}}\) = typical fraction of energy used at night
- \(\bar{P}_{\text{load}}\) = mean power during nighttime use (W)

**Linear model for user behavior**

We use exploratory analysis (e.g., isolating days when users start the night with a full battery, and estimating descriptive statistics for the following evenings of use) along with econometric modeling to understand the response in user behavior to differences in available energy. The econometric specification we use is a two-stage instrumental variables model identified in equation 4 below. The first stage predicts the state of charge of the battery at the end of the solar charging day by the available solar resource, and the second stage estimates the influence of these variations in battery state of charge on nighttime patterns of use. We choose this specification because the use of energy in the evening after variable levels of battery charge is essentially a repeated “experiment” to determine the preferences for energy service drawing on a scarce resource. By including an interaction term for the solar management classification, we can interrogate the hypothesis that solar mounting classification does not have a significant influence over preferences for utilizing energy in the presence of exogenously imposed scarcity. In the solar module data analysis that we used to estimate the model parameters, the standard errors are HC1 robust and clustered at the individual level (implemented in R, see supplementary material for more details).
Equation 4: Two stage least squares / instrumental variables approach for estimating elasticity of demand based on variation in available day-to-day supply

\[ SOC = \beta_1 R_d + \beta_2 R_d M + \beta_3 M + \epsilon \]  
(first stage)

\[ E^* = \beta_4 SOC + \beta_5 SOC M + \beta_6 M + \epsilon \]  
(second stage)

where:
SOC = the state of charge at sunset (\(SOC\) is the imputed SOC based on the first stage)
\(R_d\) = the daily solar resource
\(M\) = the management practice classification
\(E^*\) = an energy service metric (e.g., hours of use or mWh of use)
\(\beta_i\) = regression coefficients
\(\epsilon\) = model error

Results

Our results trace a conceptual path that is informed by qualitative surveys, focus group, and field observations. Remote system data improves on the status quo for monitoring systems during use for lifetime and service level estimation, showing nuance on day-to-day patterns in use and illuminating the reality of how user behavior drives the ultimate service to a greater extent than natural variation. We show how one particular element of behavior, active management of solar modules that is undertaken by half of those in the sample, leads to differences in outcomes related to the quantity and reliability of electricity, among other drivers. Reliability in particular is shown to be key for understanding the trade-offs being weighed by users, and we develop a set of reliability metrics for off-grid power that are comparable to grid-based metrics, showing that in aggregate customers choose to use lower quantities of more reliable electricity service than what would result in a purely service-maximizing framework. During our interrogation of the validity and generalizability of the results, we use a behavioral model to estimate the influence of exogenously imposed resource constraints (variation in solar energy) on use patterns, and show that demand is elastic to energy supply availability. Overall, we show how remote monitoring data can be analyzed to inform both pragmatic and theoretical inquiry on decentralized solar energy systems.

Remote data for system monitoring

Remote monitoring like that included in the PAYG system we studied enables new visibility into fleets of decentralized power systems in the field. Figure 6 includes a range of panels that illustrate one overall view of the available data and outcomes of the analysis.

PAYG is centrally motivated by providing access to financing for solar. In spite of dramatic reductions in the levelized cost of providing energy service as shown in Figure 6a using methods
presented in Phadke et al. (24), the up-front cash sales price for superefficient solar home systems that provide service like the SHS we studied is prohibitive for many households, often $100+. With a lower down payment and ongoing small payments, more people can afford and choose to buy PAYG systems. The overall cost of energy service is increased to the customer (through financing and mobile money fees), but this is exchanged for the option value on future payments, thereby spreading risk for system failure to meet customer needs between the customer and distributor (13). The stylized payment stream in Figure 6a could represent the payment stream of one of the customers in our sample who purchased in November 2013. In practice, however, payments are often more variable, including times when the system is in default or surplus of available days of use. Because of mobile charging fees (and presumably the costs in mental effort and transaction time) associated with virtual payments, there are incentives to make larger payments more infrequently than small frequent payments. Over the course of a year, someone who pays for their system essentially on time can stop making payments, and energy service remains unlocked.

During operation, if the systems were exposed to the “standard conditions” (34) used for laboratory testing and global results dissemination the household would be exposed to 5 kWh/m²/day in solar resource, and with a 5 watt module and 20% losses for electrical and other loss, 20 Wh of electricity is available (using a simple version of Equation 1). These benchmark levels (shown in Figure 6b-c) are the basis for global ex ante estimates for solar resource and service level without additional information about where products are distributed and used. In practice, the estimated solar resource among all the units in our remote monitoring sample is illustrated in Figure 6b, with a locally smooth fit line. The true solar resource was higher in Kenya than the global standard day (during this particular year, which is indicative of typical years). If this solar resource was captured and put to use fully by the units in the sample, the mean outcome (shown as the dark line in Figure 6c) would be expected to track with the resource. The sample grows through the period of record (Figure 6d), since units were randomly selected (not oversampled in times when fewer units were operational). The actual outcomes in terms of energy generated and used over the sampling period show that users have widely divergent patterns of day-to-day use and typically do not maximize the quantity of electricity produced and consumed. Rather, the overall trend is divorced from variation in the underlying solar resource and driven by habit and preferences for service. Most people use substantially less electricity than what is theoretically available, with a mean of 70% captured and used.

Part of the reduction in energy service from the fleet of SHS comes from days and nights when particular systems are not used. Figure 6e shows that roughly ¾ of systems that are deployed are actually used on a typical night. We do not have data on coincident repayment status for the systems in the sample, but it stands to reason that a significant fraction of these inactive systems are in a state of arrears and are deactivated (others simply may not be needed on that particular day). In work with another firm offering PAYG in Kenya (SunnyMoney), we found that 20% of lamps were in a disabled state during and after the payment period (13), which is on the same order as the percentage of systems we observe that are not in use on a nightly basis here.
Figure 6a-e: A set of time series plots illustrating the purchase and use dynamics for PAYG systems. Panel A shows a set of representative retail prices for off-grid solar home systems similar in capabilities to the SHS in the study with different combinations of year and appliance efficiency class. The green bars show how the M-KOPA PAYG approach offered during the study compares, with a hypothetical down payment in November 2013 followed by a series of payments equal to US$0.58 per day until the cumulative total paid is $244. The series and the cumulative sum of payments are shown as light green lines (one constant and the other the running sum). The dark line above the running sum includes expected fees to the mobile phone provider. After approximately a one-year series of payments (shown in the time series the sum total paid is US$244) the unit remains unlocked. In Panel B, the black line in the background is the “global standard solar day”, 5 kWh m$^{-2}$ day$^{-1}$. In comparison, the solar resource estimated for each system is shown in yellow (weekly averages) and the (dark red) line of best fit is estimated using a loess estimator. Panel C includes a translation of the standard solar day and the country-average to potential...
electricity generation using a simple energy balance model assuming full resource capture and an 80% total loss due to electrical and other efficiency losses. Our estimates of weekly average electrical service are shown in Panel C as well, grouped and colored based on the solar management practice classification. Our sample is shown in Panel D according to how many individuals were active. Our minimum requirement for sampling (which occurred in November 2014) was that the system should be at least four months since it was deployed, which causes the apparent plateau in the time series at July 2014. Panel E shows the average fraction of units that are used at all during evening hours day-to-day, representing the effective continuous service provided by the fleet.

USER MANAGEMENT OF SOLAR MODULES
Informed by the survey results, we used a classification algorithm (described above and detailed in the SOM) to classify patterns of solar management in the remote monitoring dataset into two categories: permanently mounted and frequently moved. Based on this analysis we find 50% of users are in each category of practice.

We show the implications of different user management practices for solar and loads in Figure 7. The figure shows how frequent moving of solar diminishes the available solar resource, mainly due to variation in the number of hours a day the module is outside in the sun, with approximately 30% losses in solar potential and manifesting as a difference in peak electricity available (if all of the available sun is captured during illuminated hours) of 6 Wh / day, enough to keep two standard phones charged or a light shining for several hours. The difference is diminished in practice because the solar module is sufficiently large compared to the battery and typical load management strategies that the battery often fills, resulting in curtailment of the solar module and effectively lost potential to charge batteries or power loads. The difference in medians between the two groups for energy captured as electricity is 11.6 vs. 14.1 Wh, a difference of 2.5 Wh, or, 18%. Much of this difference in energy accessed is manifested during daytime service, where those with permanently mounted solar use 2 Wh more, a 25% advantage. A night, the difference in energy use is smaller, about 10%, for both the energy consumed from storage and the duration of use at night. One interpretation of this is that users who frequently move the solar module engage in energy conservation behavior during the day to ensure sufficient energy is available in the evening. Another is that there is simply a wide variation in practice between users, and those with lower energy use needs and preferences are more likely to move the solar module around. Figure 8 shows the dynamics for two randomly selected individuals (one in each solar management class), as an example of the diversity in user outcomes in the data.
Figure 7: This tableau shows the dynamics between solar module management practice and load management leading to the availability and use of electricity. The Sankey diagrams on the left trace a conceptual model of the energy system; the width of the bars is proportional to the energy flow as indicated in the legend. The nodes of this process represent key steps where we show the difference between the dynamics for users who frequently move their solar module vs. those who have it permanently mounted. For most nodes there is a box plot indicating a comparison between the two solar management classes along the energy dimension (Wh) indicated on the Sankey diagram or along key influences of the energy system outcomes. We note the following for the boxplot panels: a) A uniform generation system efficiency factor of 80% is included to rescale the maximum solar generation estimates based on peak power PV production, accounting for loss due to temperature, operating away from the true peak power point, and losses in circuits. d) The expected solar generation is based on a linear model to parse daily solar resource into hourly values, filtered through hours when the solar module is actively generating, and assuming a horizontal module placement with no shading. f) The daily energy stored (and used) is based on detailed measurements of the battery current and voltage. f) We neglect the efficiency of the battery in the analysis and note that it is generally a small loss compared to the underlying uncertainty in estimates (losses on the order of 5% in
lithium batteries in off-grid solar applications like this one, see SOM5) g) The hours of use during lighting hours is the sum total number of non-daylight hours that the system is using power above a small threshold level for background consumption (0.1 W). It is a measure of the highest mean number of hours lighting is used at night and in the early morning by the systems.

Figure 8: The variation in average service between two individual systems, one each randomly selected from those that are classified as permanently mounted and frequently moved. The figure in the same format as Figure 7, but with box plots replaced by individual point estimates for the typical day for each user.
OFF-GRID POWER AND RELIABILITY

Two key drivers of reduction in the quantity of electricity used were curtailment of solar charging during periods when the battery is full, and under-utilization of the full available charge in the battery overnight. These reductions in quantity are directly related to increased effective reliability of power from the system (i.e., the fraction of time that loads can be powered, and the predictability of outages). The opportunity to improve reliability arises partly from the design of the particular SHS in our study, with solar modules that are oversized compared to the central storage battery and loads on typical days, providing adequate power for days with a smaller solar resource availability (either due to natural causes such as clouds or due to user behavior such as leaving the module inside).

An engineering-based model for energy utilization (e.g., the model in Equation 1) might assume full capture of available solar energy and full use of the peak available energy by householders (resulting in most mornings with empty batteries). In practice users manage their systems much more conservatively, and the median likelihood of reaching an empty battery on any given day is 10% across the full sample. Figure 9a shows a metric similar to SAIDI, the number of hours a year where no power is available. We define and estimate this metric as all hours where the battery state of charge is below 2% of the minimum level. SHS reliability is highly specific to user practice, with some users experiencing reliability (as measured in this case) on comparable levels to some grid-based power. Others have frequent and long outages. The median SAIDI in the sample is 200 hours per year. As a counterfactual, we also computed what the SAIDI would be given the standard model of user behavior: maximizing the energy consumed each day. In that case, the expected median SAIDI is 1,700 hours, implying users prefer to experience 90% more reliable power in practice than what would be suggested by an energy-maximizing model.

While it is tempting to simply compare grid connected and off-grid reliability across dimensions like SAIDI there are important differences as well. While outages on the grid are beyond the control of individual users and exogenously imposed, the users of standalone power systems have direct control over procuring and provisioning resources with natural exogenous variation in availability, improving reliability both in terms of reduced durations without power and preferential timing of the outages. Informed by user feedback displays (like the one on the M-KOPA system), it was possible for most users to maintain a reserve buffer of energy to prevent outages most of the time, and almost always during the day. Off-grid outages may be less inconvenient than those on the grid because users have a degree of control and predictability. The patterns of outage over the course of typical days are shown in Figure 9b. Most “outages” for the off-grid power systems we occur very early in the morning before sunrise and infrequently during peak sun hours of midday. At the beginning of the evening on a typical day, less than 1% of systems are in an outage condition, with peak outages, at 7%, occurring just before sunrise.
Figure 9: (A) Reliability metrics for off-grid power systems (n = 1112). The effective seasonal average interruption duration index (SAIDI) is shown as cumulative distributions (in log10) in panel A for the two solar management classifications we estimated. (B) The typical hourly pattern for reliability. NOTE: there is no monitoring available for the state of charge for other batteries in the system, such as those in mobile devices or portable lamps. The actual period when no power is available in any of the devices for light and/or communication is by definition less frequent (more reliable) than the SAIDI equivalent observed at the central storage battery.
VALIDITY AND GENERALIZABILITY OF RESULTS

Our analysis rests on assumptions and interpretations of the empirical results, with some of the critical ones listed and interrogated in this section. Additional figures in support of this analysis and the documentation for implementing the statistical methods are in the supporting material, including commented code notebooks for the full analysis.

1. Our interpretation of the results is that those who move their solar module do so primarily due to perceived security concerns (as indicated by qualitative results in the survey), and this significant response to exogenous security risk is additive to the underlying endogenous variation in the needs and time preferences for service.

Considering the evidence, we find that the most likely interpretation of variation we observe in solar management practice derives from differences in the perception or sensitivity to security risk. This variation in access to service leads to lost opportunities as a result of exogenously imposed risk (e.g., from higher population density or proximity to low security areas), mediated by individuals’ perception of it.

Active management of a solar module is an added cost of ownership in time and mental effort, requiring users to balance maximizing the value of energy service in the short term (day to day) and minimizing the risk in long-term deprivation from theft. The survey revealed that of those who report moving their module indoors, the mitigating factor was overwhelmingly security concerns (78% of respondents) followed by those who intend to permanently mount soon (8%) and other infrequently reasons offered by only 1 or 2 respondents each (frequent moving of the whole system, poor solar exposure, fear of rain, cables too short to mount, etc.). Only one user indicated that they “liked” moving the solar module frequently, and it stands that the cost in time and attention for active management is one most users would prefer to avoid.

Given the location estimate precision (we expect our method is precise to roughly 10 km scale) we do not expect nor do we see visual patterns of security disparity when individual systems are mapped by classification. The clusters of insecurity one might expect to find in urban vs. rural and peri-urban areas occur on finer scales typically than 10 km. In bulk, however, differences in expected population density are significant. Those with permanently mounted systems appear to live in somewhat less populated areas, and the density of population is ~1/3 higher for people who frequently move their systems. This is also consistent with the survey results, indicating higher population density (and typically attendant theft risk) may lead to perceived or real risks of loss.

One possible alternative hypothesis is that security concerns are actually felt equally by most, but that the people who frequently move their solar module do so not from an increased perception of risk but because they have lower energy needs (thus the ~20% reduction in energy use is self-directed rather than exogenously imposed). If this were true, we would expect that those who permanently move their solar module to have systematically different (and lower) needs for energy than those who permanently mount the module in spite of the risk. A test of this is
observing behavior for users who start the night with a full battery. Figure 10 shows the distribution in outcomes for both groups, which are very similar. The duration of energy service over night is 3.3 hours for users with permanently mounted classification and 3.6 hours for those who frequently move the solar module. The electricity use data, therefore, do not support this alternative hypothesis.

Our survey also indicated little-to-no statistical difference between individuals who were classified in the two solar management practices across key indicators that are expected to drive energy demand. The incomes, broad classes of livelihood type, total status quo spending and fraction of income spend on energy, and household size are all not significantly different between the two management classes (detailed results of statistical tests for independence are in the supporting material).

We use econometric techniques to test a more nuanced model of user behavior, testing how fluctuation in available energy manifests to differences in behavior. We developed an instrumental variables (IV) two-stage linear model using the day-to-day solar resource to predict the battery state of charge as an exogenously imposed “first stage instrument” that pseudo-randomly assigns likely battery charge each evening. This estimate is compared in the second stage of the analysis to a range of metrics, including the hours of use and total energy used. Note that this is not strictly a causal application of IV because the instrument in this analysis (the daily solar resource) could plausibly influence use patterns at night through a channel other than the battery state of charge in the evening (e.g., on sunnier days, more devices could be more fully charged during the day, potentially reducing the need to charge at night, or anticipatory behavior of sunny or cloudy days influencing energy use at night).

In the IV model results there was no meaningful difference between the dynamics of energy use between the groups. As an example, the regression results table (Table 2) shows the results for an IV estimate of the influence of evening state of charge on nighttime use profiles, with the solar management classification factor carried through the analysis as an explanatory variable. People with permanently mounted modules have no statistically or practically significant difference in behavior, with a 6% lower baseline load (not significantly different from 0) and have a response 3% more sensitive to increased state of charge. The second stage coefficient for the main effect (state of charge influence on hours of use) is positive, indicating that even on sunnier days with greater opportunity to recharge devices during the day, energy use increases in the evening.

Overall, individual systems classified as “frequently moved” were in areas with higher population density, were less likely (but not significantly) to be owned by a farmer, and were slightly more likely to be owned by a business person. None of these factors however is sufficient for concluding the two groups have different energy service needs, and two specifications for behavioral modeling (a simple one based on nights starting with a full battery and a more complex IV specification) showed no significant behavioral differences with respect to the two groups. Taken together with the survey results that resoundingly indicate theft is a key
concern for those who move their solar module, we reject the alternative hypothesis that underlying differences in energy need are the key driver for solar management practices in favor of a hypothesis that it is the underlying level of theft risk that influences those decisions by users.

Figure 10: Distribution in the overnight hours of use on nights where the battery starts out full (>93% charged), split by solar management practice.
Table 2: Regression results for instrumental variables analysis, predicting the change in energy used at night (mWh) based on changes in the available charge in the battery (mAh), instrumented by the daily solar resource. The standard errors are clustered at the individual level and HC1 robust to heteroskedasticity. Solar mounting classification (a two-level factor) is interacted with the model to test if there are significant improvements in the result by including it (i.e., a test of whether the users display significantly different behavior in the face of varied availability of energy).

<table>
<thead>
<tr>
<th>Solar Classification (Perm. Mounted = T)</th>
<th>-83.166</th>
</tr>
</thead>
<tbody>
<tr>
<td>State-of-charge at sunset (mAh)</td>
<td>2.568***</td>
</tr>
<tr>
<td>Interaction term: Classification x State-of-charge</td>
<td>0.094</td>
</tr>
<tr>
<td>Constant</td>
<td>1,194.403***</td>
</tr>
</tbody>
</table>

Dependent variable: Energy Used at Night (mWh)

Note: *p<0.1; **p<0.05; ***p<0.01

The F-statistic for first stage is 8592 on 364443 d.f.

2. We assume the users in the dataset are representative of M-KOPA customers in general.

We were careful in ensuring that the sampling used for customers in the survey and in the dataset for analysis are representative. The first half of survey customers was mis-sampled using a technique that was not random along the dimension of purchase date (an analyst mistakenly drew sequentially starting from a randomly chosen start point based on the “time of database entry initiation”). The second half of survey customers were randomly selected using a draw based on randomly assigned account numbers. Analysis presented in the supporting code notebooks indicates that no meaningful differences were observed between the groups, so both are included in the survey analysis. For the ~1,000 customers who were not surveyed, each was randomly selected based on account number as well. Thus the customers in our dataset are representative of the users for M-KOPA at the time, circa June 2014. At that time, the sample we received was approximately a 1 in 100 sample of the company’s full user-base.

3. We posit that our findings in the context of Kenyan M-KOPA users are partly applicable more broadly to off-grid solar users in Kenya and elsewhere, but with important context and caveats.
The Kenya case is somewhat unique for off-grid energy and PAYG in particular. Kenya’s early solar market was a developing world leader \((15)\) and remains one of the largest off-grid solar markets (and was a pilot country for Lighting Africa, a market support program for off-grid solar, starting in 2008), but other regions are newly emergent and clearly show the potential to replicate (and surpass in the case of the Bangladesh SHS market) the success of the Kenya market. Kenya is also a leader for mobile money with the highest global use rates (~60% of people use mobile money for day-to-day transactions \((27)\)). Again, other countries and regions show promise to have similar access and use rates for mobile money, which depends on the regulatory environment, telecommunications sector structure, the level of wealth in the economy and cultural norms.

Along other dimensions (income, stability, electrification rate) Kenya is often in the middle of the distribution for the developing world, but relatively affluent in the context of Sub-Saharan Africa. This combination of a robust and well-supported solar market, relative affluence, and early mobile money penetration made Kenya the home of the highest number of PAYG firms operating globally circa early 2015, by a factor of two \((13)\). It remains to be seen if Kenya is a proving ground for energy access systems that can be replicated and expand quickly to meet the needs of the global poor or is an isolated and special case. The expansion activities of PAYG firms that are active in and around Kenya, East Africa, and more broadly suggests the former.

The architecture of the M-KOPA product is a pico-solar home system with a fixed-point battery connected via a cable to a remote (and relatively lightweight / easy to move) solar module. This type of system is common, along with configurations that integrate the lamp with the battery. We expect the dynamics of moving lightweight solar modules that we observed for the M-KOPA product are representative of all similar products that use this “separate solar module” architecture, provided that the context in which the products are used does not differ widely. Additionally, roughly 100% of users will actively manage devices with integrated solar modules that are directly attached to batteries (and often lamps), e.g., the d.light S2 pictured in Figure 1c. For these devices daily movement is the norm, and the risk of theft is amplified because a fully functional and portable system is necessarily exposed to sunlight during recharging.

The driver for active solar management in this case, insecurity, may be more broadly applicable in Kenya and the developing world. There is a long history of concern around theft of off-grid solar modules \((15)\), and people who use off-grid solar are often at the margins of society where security concerns can be exacerbated by inequality and poverty. As off-grid solar becomes more widespread, it is possible that the theft pressure will be reduced on solar modules if they become an everyday commodity rather than a status symbol. Or, the concerns could grow if a vibrant market for used (and potentially stolen) solar components emerges in response to the availability of goods on legitimate secondary markets that one would expect to emerge for any commonly used electrical appliance.

The M-KOPA product’s unique energy system sizing means it is in many ways a “best case” or “forgiving” system for users who do not optimize solar energy generation. The solar module is
over-sized compared to the battery capacity and typical daily resource (on a “standard” solar day with 5 kWh/m$^2$ resource, the module can approximately recharge the battery fully and have $\sim$20% extra energy), leading to frequent curtailment of solar charging in the afternoon particularly among those with permanently mounted systems and a reduction in the influence of user management on nightly availability of energy. Additionally, the M-KOPA system has user feedback on the battery state of charge (a battery charge indicator similar to those used in mobile phones) that helps users understand and optimize management.

Thus we expect that the dynamics we observe for user management of solar is representative and typical for off-grid energy users who live in places with security situations similar to Kenya and who are using devices with easy-to-move solar modules. The reduction in service may be amplified in the case of products that must be moved daily (or with smaller, easier to move solar modules). Also, for products with smaller solar modules relative to the energy storage capacity, we expect the disparity in effective solar resource caused by user management of the solar module to not be reduced as it is in the M-KOPA systems, and we further expect this to result in a larger disparity in the level of energy service achieved. Furthermore, M-KOPA systems and others like it that are expandable could effectively reduce variation in service availability in the early period of use but later become a more binding constraint on service as more appliances and devices are added to the system.

**DISCUSSION**

**DESIGNING DECENTRALIZED ENERGY SYSTEMS**

Our analysis explores technology-human systems fundamentals that are at play in supplying reliable service with off-grid power systems. Traditionally the design fundamentals for off-grid solar have been in response to relatively expensive PV modules and inelastic design loads, sizing the battery to manage natural variability in the resource with a common heuristic that the battery should provide two or more “days of autonomy” for the loads. The SHS systems and users we studied (d.light D-20g distributed by M-KOPA) are instructive for understanding the fast evolving technology architecture for decentralized power systems.

The results demonstrate the implications of recent and rapid shifts in the efficiency of end-use technology (*superefficiency* trends) combined with declining costs for PV and advanced batteries, which enable new architectures in power system design with distributed storage in portable ICT and lighting devices. Photovoltaics were once the most expensive element of standalone PV systems, and a system design practices placed a great deal of emphasis on sizing the module so as to minimize its impact on the cost of the system. In the last 10 years the cost of PV has reduced by 90% (24) and the design of modern off-grid solar electricity systems now often features much larger solar PV modules compared to the central storage battery capacity. Increased generation capacity enables extra power for coincident recharging of devices with onboard batteries and still provides reliable service across day-to-day variation in solar resource
and place-to-place typical resource levels. The configuration results in curtailment of solar charging on sunny days (as was in the dataset), but it also improves the user-experienced reliability with regard to power availability on days with a smaller resource and in cases where solar module management impacts the effective resource.

Another pressure towards larger PV modules is to create opportunities to power unknown user-supplied loads (including many with on-board batteries). In a sense, off-grid solar users who charge mobile phones, portable lamps, rechargeable radios, tablet computers, etc. are using a distributed battery storage system that is larger in practice. While the capacity of the central storage battery was about 18 Wh in the M-KOPA product, we estimate that on a typical day only a fraction of this capacity is used (roughly 6 Wh) and that ~7 Wh is coincident used during the day.

Preconfigured systems that are designed to be reliable across a range of operating regimes (as opposed to designed for a specific place) means that for many locations on many days there is excess energy. Rather than viewing this as a shortcoming in the design of systems (relying on legacy heuristics that solar electricity generation from the installed PV should be maximized), an interpretation in the context of inexpensive PV and distributed storage is that it is appropriate and expected that on the majority of days there is curtailed solar electricity, reflecting shifts in the least-cost strategy for providing electricity that meets peoples’ reliability needs for different applications.

**Evaluating Off-Grid Power Systems**

The diversity we observe in accessing energy service highlights the difficulty of measuring and supporting access to energy through binary metrics of “on/off” grid or with/without SHS along an “energy ladder” framework. Some grid users (10% of the customers in our survey) chose to add a SHS to their ostensibly connected household to increase reliability (rather than monotonically searching for higher power service as the energy ladder suggests), and we observed a great diversity in user practice that influences the energy services provided by decentralized power systems. Here we highlight ways that our results inform approaches of enterprise and policy for providing access through ICT-enabled decentralized energy systems.

A joint framework for considering the service quantity and reliability of power, linked with human development benchmarks, could help better-focus support in energy access projects and policy. An emerging global framework for assessing energy access benefits (*UN Sustainable Energy for All*) would largely rely on relatively costly ($USD 10+ per household) ex ante predictive engineering estimates that result in relatively coarse and widely spaced (in time) access predictions (16). As new datasets become available they could be a powerful tool for ex
post monitoring to verify and improve the ex ante estimates, through frameworks like those presented in Figure 6 of the results.

Decentralized system lifetime (long-run reliability) is a particularly difficult metric to estimate ex ante for fast changing, emerging technologies that are used at the edge of the grid. It is also critically important for estimating the overall benefit from supporting distribution and use of off-grid power devices, since human development benefits are only accrued if the system or components are in use. The product lifetime, however, depends on a complex combination of factors including technical degradation of electronic components, environmental exposure, user care, and eventual obsolescence from the availability of superior alternatives. Remotely monitored systems may provide a reliable signal for tracking the lifetime of systems in the field and responding to failures.

Furthermore, during the operational lifetime the short-run hourly and diurnal reliability of power is a key element of design for electric power systems of all sizes, from large-scale grids to pico-power systems. To effectively focus effort towards human development with expanded access to electricity, it will be important to measure metrics that go beyond the magnitude of service provided (29), and both short- and long-run reliability of service are critical elements of the ultimate value of electricity service. In our analysis we showed how a user-driven form of SAIDI reveals the ways people using off-grid power systems prioritize and allocate energy service, pushing outage times to very early morning hours.

Ubiquitous connectivity and monitoring could help measure off-grid power reliability and focus support for users, identifying opportunities for improvement in system design along with broader policy support that is appropriately scaled given the value of reliable power. Public reporting for reliability metrics is currently sparse, however, for on-grid applications (often only appearing deep inside consulting firm reports) and virtually nonexistent off the grid. It is within the technical capabilities of both grid-based and off-grid operators to track and report on a much finer scale than the status quo, and we show how finer resolution in tracking (hourly, by customer) available from connected off-grid power systems can lead to insights about the diversity of customer experience.

Other evaluation applications that support users with more reliable service include electrical system health monitoring, with focus on large components that maybe subject to degradation and failure—batteries, PV modules, and balance of systems. In the data we analyzed the median battery efficiency observed was 95%, demonstrating high performance for the LiFePO₄ cells (with nearly all the systems in their first year of service—so little expected degradation). However, a small minority of <5% of users experienced lower efficiency in the range of legacy PbSO₄ cells, around 75%. Data-driven targeting for maintenance (and monitoring for long-run checks on manufacturing practice and component batches) could improve the efficiency of support for users.
EXPANDING OFF-GRID ENERGY SERVICES

Our analysis showed that in spite of natural variation in solar energy and user-mediated variation from solar management, the architecture of the system (ratio of solar module size to loads and storage) enabled relatively reliable power. Most of the users we talked to in the survey, however, are also interested in additional types and quantities of service (i.e., expanding access across multiple dimensions with energy stacking(43)). When they were asked about what they would like to upgrade about the system, users offered free-form responses that indicate expanded and new service is highly valued. Over 60% of the respondents would like more or better lights (at ~170 lumens the M-KOPA has roughly 10x higher light output than incumbent kerosene lighting but still is far less bright than typical lighting on the grid, which is on the order of 1,000’s of lumens). The second most frequently mentioned upgrade (~35%) was to add a television, and the power consumption of the most efficient color TVs on the market is currently on the order of 10 watts for a 19” unit. Combined with increasing energy demands for mobile telecommunication devices (concomitant with smart phone adoption), these increases in service will require both new appliances and new power generation and/or storage capabilities to meet those needs while maintaining the same level of reliability. Adding additional load to the system without expansion of the energy system would stress the solar and battery capacity of the M-KOPA system, and few users (less than 10%) mentioned explicitly that they would like to add larger solar modules, batteries, or other components as part of an upgrade.

Maintaining the reliability that users have demonstrated they value while adding service will thus likely require packages of appliances and expanded energy systems that either replace or augment the legacy system. Achieving these energy ladder transitions while maintaining customer satisfaction with the system could be challenging. For example, many customers report that the solar energy system is a status symbol, and it leads to feelings of improved standing in their community. Asking them to part with a valued system that was carefully paid for over a year in order to add capabilities for extra appliances may be difficult. Going forward, data from remote systems grounded in field-based qualitative research can help inform ways that different PAYG business model approaches (e.g., energy fee-for-service vs. micro-loan(13)) can balance initial system size to keep initial costs low for customer acquisition while leaving room for variation in practice and future load growth.

INFORMATION SYSTEMS AND CLEAN ENERGY DEVELOPMENT

Our work demonstrates the potential value of remote system monitoring data for research on the user-dynamics of energy access, a critically important element that bridges between technical and social domains that jointly support energy access (51, 52).

Using personal data from energy systems for these and other goals is increasingly understood as sensitive from an end-user perspective and simultaneously valuable to businesses and aid
organizations. Identifying the degrees of value available and the distribution of benefits is an emerging need for research focus to inform how to manage these emerging information resources (39). Focus group participants we heard from in Kenya indicated they see the value in data capture and analytics by firms and organizations that distribute off-grid energy systems, but they were strongly against sharing raw, personal data between organizations due to fears about security and uncertainty around potential risks. The results of our study highlight the day-to-day environment of risk that is experienced by many off-grid power users, one of several important cultural and social factors for the broader understanding of energy access dynamics.

Off-grid power systems serve people on the margins who are isolated along political, economic, or geographic dimensions (6). With appropriate safeguards and control, there are a range of possibilities to improve system design, maintenance follow-up, monitoring for public policy priorities, and other applications of newly available data. These information-energy nexus approaches could accelerate and strengthen a global effort towards eradicating deprivation from modern electricity.
CHAPTER 4 REFERENCES


44. Posselt, Rebekka, Müller, Richard, Stöckli, Reto, Trentmann, Jörg, CM SAF Surface Radiation MVIRI Data Set 1.0 (2011), (available at http://dx.doi.org/10.5676/EUM_SAF_CM/RAD_MVIRI/V001).


Supporting Material for Chapter 4

Off-grid solar energy services enabled and evaluated through information technology

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August 31, 2015

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Peter Alstone, Arne Jacobson, and Daniel M. Kammen
CODE NOTEBOOKS AND SOURCE DATA
The core analysis for this work was completed using the R programming language and rendered in a marked-up “code notebook” using the knitr package. These code notebooks detail the specific code and algorithms in a transparent format. The notebooks are available online at: https://zenodo.org/record/31924

DATASETS
The core data we include in the analysis are described in tables S1 and S2 below. After the tables are details on the approach and contents of the data. The geographic coverage of our sampling is shown in figure S1 below.

Table S1: Key primary data supporting this work.

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Includes</th>
<th>Notes</th>
<th>Sample Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Randomly selected M-KOPA customers: main group</td>
<td>Remote system monitoring.</td>
<td>Chosen with random draws of customers with systems that were active</td>
<td>995</td>
</tr>
<tr>
<td>Geographic oversampling in the Kericho and Sitotwo regions</td>
<td>Remote system monitoring.</td>
<td>Chosen to compare with benchmark pyranometers.</td>
<td>400</td>
</tr>
<tr>
<td>Surveyed customers</td>
<td>Remote system monitoring; telephone survey results</td>
<td>Surveys conducted by M-KOPA staff with in-person collaboration from the UC Berkeley research team.</td>
<td>175 (160 completed)</td>
</tr>
<tr>
<td>Pyranometer – short term solar radiation monitoring</td>
<td>Global horizontal solar radiation on 5-minute time interval</td>
<td>Installed by research team for temporary monitoring</td>
<td>~ 3 weeks at each of two sites in western Kenya.</td>
</tr>
</tbody>
</table>
**Figure S1:** Locations of the systems with remote monitoring datasets, with facets for the sampling category (clustered around pyranometer stations, random without surveys, and those who were surveyed, another randomly selected group). On the pyranometer-adjacent facet there are crosses indicating the locations of the two pyranometers. The reason that the systems in that plot are not as tightly clustered around the pyranometers as one might expect is that the sampling for these systems was done only based on the location of the most recent mobile phone tower used for communication. In reality a number of mobile phone towers are used by each system, and in many cases these are widely distributed.

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Includes</th>
<th>Notes</th>
<th>Sample Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Satellite-based solar energy</td>
<td>Daily estimates of solar radiation on a 15 km grid.</td>
<td>From CM-SAF, operational data product for surface-incoming shortwave radiation, for establishing the daily energy available.</td>
<td>Covers relevant study area and time period.</td>
</tr>
<tr>
<td><strong>estimates</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hourly solar energy estimates</td>
<td>Hourly estimated solar energy derived from satellite and weather</td>
<td>Part of “SWERA”, a UNEP program for solar and wind energy data, these are used to distributed daily estimates of insolation over the hours of the day.</td>
<td>3 years (2000-2002) over 32 sites at hourly resolution.</td>
</tr>
<tr>
<td>in Kenya</td>
<td>observations.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kenya population density</td>
<td>Persons per square kilometer, on the basis of census locations (the</td>
<td>Provided by the World Resources Institute as a processed GIS datafile in support of a report on the country (47).</td>
<td>Population density in 6,622 defined areas (median population of 3,100 in a median area of 16 km²).</td>
</tr>
<tr>
<td></td>
<td>smallest available demarcation of area) from the 1999 Kenya census</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**Sampling Frames for Surveys**

The sampling frame for the survey participants was partly conducted using inadvertently structured samples, and partly using truly random samples. The first 85 customers were sampled based on the date of purchase (an accident made by a data analyst), which resulted in oversampling clustered for date of purchase in a particular 1-3 day window in early April 2014. Once this became clear, the remaining 90 were sampled based on a draw from account numbers that are generated by a random algorithm, with the date of purchase sufficiently old that the system has been active for at least 6 months. An ex post analysis (detailed results in the code notebooks) of the customers in each sampling frame revealed that in spite of the error in sampling, it is reasonable to include all of the respondents in the analysis. The level of deviation in results between the two sampling frameworks is insignificant in most cases and we find no reason to question the overall validity of results as they have been interpreted in this work.

**MKOPA Pico-Solar System Monitoring**

These data are gathered automatically by M-KOPA using the onboard machine-to-machine GSM chips that are included in every unit. There are two core datasets: system status and location. The status data are recorded once an hour (approximately), and include the following primary measurements: battery voltage (mV) and current (mA), the internally estimated state of charge of the battery (mAh), the voltage of the solar module (mV), and the timestamp. These data are transferred approximately once a day, along with meta-data that identify each system using unique GSM chip IMEI codes, identify the time of data transfer, and the latitude and longitude of the mobile phone tower used to make the transfer. The sample we obtained includes 1,025 randomly selected customers from throughout the M-KOPA system, beyond those included in the survey.

**Uncertainty in Location:**

The estimates we have for location likely have an uncertainty on the order of 10 km, based on heuristic rules of practice for obtaining location information based solely on the presence of data connections with particular mobile phone towers and patterns we observe in visual analysis of siting. A key question is whether this source of error is likely to influence our results. Our analysis relies on location estimates for estimating solar energy available for access. Figure S3 shows an area where our team has particularly good knowledge about the geography, near Kericho, Kenya. P.Alstone has lead market research there (among others who have done work) in 2009, 2012, and 2014. It is notable here that there are fewer estimates in location to the southeast of Kericho, where there are large tea plantations (lighter green uniform crops) and protected forest (darker green). To the north and west there are far more small landholders and outlying town centers. The rough matching of system location estimate to a heuristic based on relatively good knowledge of the area is encouraging with respect to the precision of the estimates being approximately 10 km.
Figure S3: Locations of SHS (estimates indicated with black points) on a satellite / road hybrid map (from Google) focused around Kericho, Kenya where our team has conducted field research on the market for solar since 2009. For interpretive reference, each 0.1° in Longitude / Latitude is approximately 11 km, and the points here represent approximately a 1 in 100 draw from the population of M-KOPA systems at the time of this research.

The approach we take to assess error in this case is based on variogram analysis of the geospatial, satellite-based solar energy estimates. A variogram is a GIS analysis technique that helps identify spatial thresholds below which the datum of interest is correlated strongly in space and above which is essentially randomly distributed.\(^{(53)}\) For our work we use the Variogram function in R (package “usdm”) to compute variograms for each day in the solar energy dataset. The spatial extent of the analysis is cropped to the region bounded by -1.5°S, 1.5°N, 34°E and
36°E to focus the estimates on the region where most (about 80%) of the solar energy systems were deployed, the western part of Kenya (see Figure 1 in main text, and S4b for the bounding box of the variogram analysis). This focused estimate ensures that the specifics of the local topography are not lost in an analysis that is more broadly focused, including many plains areas and ocean coverage that might make the data look more highly correlated over longer distances.

The results below show that over the distance errors we expect (on the order of 10km typically) there is high correlation in the daily solar energy estimates, which indicates that error introduced with random error in the location estimate will lead to some additional variance in our results but should not obscure the relationships we observe between solar energy and energy service. Figure S4a shows 9 randomly selected days, with individual variograms created for each day. Figure S4c is an aggregate of all the days in the solar energy data set (574 days from January 2013 to August 2014), and shows the mean variogram estimate.

![Variograms for solar radiation estimates](image)

**Figure S4(a):** Variograms for solar radiation estimates (satellite derived estimates) for 9 randomly selected days. The identification code in the facet titles of the plot refers to the satellite product (SIS – shortwave incoming solar) and
the date. The color of the points is scaled according to the mean solar resource over the area under consideration (cropped to the region bounded by -1.5°S, 1.5°N, 34°E and 36°E).

**Figure S4(b):** For the same days as shown in F.S4(a), maps showing the raster estimates of insolation over the extent of Kenya, with the national and first-level subnational boundaries shown along with a rectangle indicating the bounds of the variogram analysis. The color scale represents the solar resource in kWh/m²/day.
**Figure S4(c):** Aggregate variogram analysis for the full solar daily solar energy dataset (daily estimates of mean insolation), cropped to the region bounded by -1.5°S, 1.5°N, 34°E and 36°E. Each grey trace is a single day’s variogram, rescaled so the maximum semivariance is 1. The heavy blue line is a LOESS fit of all the daily datapoints.

**PYRANOMETERS TO BENCHMARK RESOURCE AVAILABILITY**

While we conducted field research over the months of May and June 2014 our team placed two pyranometers in the field adjacent to areas where we expected significant numbers of off-grid solar devices to be located. The pyranometers were affixed to roof structures using locally manufactured brackets (see Figure S5 below where a craftsman is welding a bracket to our specification) to achieve reasonable setback and sky-views from the roofs of two buildings where they were mounted: Ray’s Place Hotel near Kericho and Sitotwo Primary School near Eldoret. Both sites were judged by our field team to have reasonable sky views with low levels of obstruction for the purposes of this study.

The pyranometers were both LiCor LI200 type, which are silicon photodiode pyranometers that are suitable for short-term environmental monitoring and particularly well-suited for monitoring the solar resource for photovoltaic generators (the silicon photodiodes are less stable than thermopiles typically used for long-term monitoring but have faster response times and more closely match the physics of the underlying photoelectric mechanism that is in action with PV. The pyranometers were connected to HOBO U12 remote dataloggers logging on 5 minute intervals using EME Systems UTA amplifiers that convert the output current of the pyranometers to a voltage matched with the HOBO loggers. The combined pyranometer-amplifier sets were calibrated side-by-side with an Eppley PSP reference pyranometer by staff at the Schatz Energy Research Center in Arcata, CA.

Figure S6 supports the text with a graphical summary of the linear relationship between estimated and observed daily total insolation at the pyranometer sites, over the period of record.
Figure S5: Craftsman in Kericho welding a bracket to mount a pyranometer to the roof of a hotel.
Figure S6: Relationship between the day-to-day solar resource based on pyranometer observations and satellite observations over the period of operation for the pyranometers.
MODEL TO PREDICT HOURLY INSOLATION BASED ON DAILY TOTAL

We use a linear model to predict the hourly fraction of the daily total insolation in each day of the satellite-derived dataset. This is a two-step process. In the first step we fit a linear model to existing solar resource data that have been estimated on an hourly basis (see Figure S7). The model we fit (specified in Equation S1 below) is used to predict the fraction of daily solar energy that falls in a particular hour based on the hour of the day and the overall daily total solar resource. Other models we tested (with additional terms) and a random forest machine learning trial to verify relevant factors are documented in the Code Notebooks.

**Equation S1**: Linear model to estimate the fraction of daily solar resource available in each hour of the day.

\[
F_{\text{hour},i} = \beta_1 \cdot H_i + \beta_2 \cdot G_{\text{day}} + \beta_3 \cdot [G_{\text{day}}(H_i)]
\]

where

- \( F_{\text{hour},i} \) = the expected fraction of daily solar energy in each hour
- \( \beta_i \) = are coefficients for the
- \( H_i \) = expected fraction available based on the hour of the day
- \( G_{\text{day}} \) = daily total added to every hour
Figure S7: A set of representative hourly solar data (5 representative days) for the 32 sites where hourly estimates were available and used to develop a linear relationship between the fraction of daily insolation in each hour and the interaction of the daily total and hour of the day. These data are originally from a detailed report on the solar resource in Kenya (46).
CURRENCY EXCHANGE RATES

The national currency in Kenya is the “Kenya Shilling” (Ksh), and is the basis for pricing the solar home system and reporting income and spending in the survey. Throughout this article we use the average foreign exchange rate for the Shilling to US Dollars over the period of record for the remote monitoring data (November 2013 to November 2014): 88 Ksh/USD. The source of foreign exchange data is the API of Oanda.com, accessed through the R package “quantmod”.

SURVEYS VS. REMOTE MONITORING FOR ESTIMATING HOURS OF LIGHTING USE

Figure S8 shows a scatterplot for systems with both estimates available and while the general distribution of data is similar (in fact, the mean ratio of survey estimate to remote monitoring estimate is one), on an individual basis there is wide variation between the survey-based estimates and actual use profiles (the “survey accuracy ratio” interquartile range is 0.7 to 1.3). In this case, the actual use is defined by the average number of hours when the sun is not up where the apparent load on the battery is greater than a threshold value that is high enough to power the main light points. The remote monitoring estimate on a day-to-day basis thus represents the maximum number of hours a light could have been used (not including use of the portable rechargeable lamp that could have been charged during the day), and in this plot the average of those day-to-day estimates is compared to the average reported use for the two light points.

Figure S8: Comparison between survey data and estimates for night-time use of light from the remote monitoring dataset. Adj. R² is 0.13 for the linear model fit, shown in blue with a grey 95% confidence interval.
Table S3 below shows the results of statistical comparisons between the two solar management practice groups, with Chi-square tests for group differences to test the statistical independence of the groups across dimensions captured in the survey. It shows that there are not meaningful differences between the two solar management practice groups with respect to income and energy expenditure metrics.

### Table S3: Contingency table for a range of survey responses based on the solar management classification.

The table was rendered using the Hmisc package in R, and applies statistical tests for independence that depend on the kind of data.

### Areas of Future Work and Extensions on the Analysis

#### Classification for Solar Window Estimation

A key assumption in the calculations we make is that the energy generation from the PV modules can be estimated using the solar module power, a derating factor (0.8), and the expected global horizontal solar radiation in each hour, only counting hours when the module is in a maximum power voltage class. This assumption fails to account for the tile and angle of the solar module or any fouling, local obstructions, reflection, and shading. With an estimate of PV module
power independent of the coincident load, one could estimate the angle of incidence and true daily generation, but this measurement is not included in the dataset.

With improved visibility and additional measurement it may be possible to use classification of the diurnal divergence in observed power from the model-estimated generation to estimate the tile and shading profile for individual modules. Figure S9 below shows the fractions of the theoretical power that are observed in each hour of the day for a set of systems. Smooth lines of fit (using LOESS and GAM models as appropriate for the sample size) are indicate potential to classify modules that likely are east-facing (those with typically > 1 fractions in the morning), west facing (vice versa with evening peaks), and relatively flat (flat profile). With additional measurement (that would come at a cost for sensing and data management) there is promise for more detailed system-level remote diagnostics.

Figure S9: A random set of 10 systems, showing the relationship between the observed power and expected power given the solar resource total and the time of day.

STRETCHING COMMUNICATION NETWORKS WITH OFF-GRID SOLAR

In the course of our work to identify system locations we found a curious pattern to observations that suggests the reach of GSM networks significantly under-estimated for connecting with M2M systems with data requirements like PAYG. Many GSM towers in the dataset made connections
with SHS that are much farther (up to ~100 km or more) than conventional wisdom would suggest is possible (35 km max, and typically <10 km for GSM, because of communication latency issues). The most recent estimates from GSMA are that 80% of the population in developing Africa is covered by a GSM network, and 60% of the off-grid population. With this reach, 40% of people beyond the margins of the grid cannot rely on M2M connections for verifying payments and remote monitoring.

Half the communication events (~$10^6$ observed overall) appeared to be over a distance of 10 km or shorter, but the distribution of distances has a “fat, long” tail, with 25% of communication over 60 km and 10% over 150 km. This is counter to the operational principles of GSM. It suggests that either the data are systematically flawed or that the connection type for PAYG allows much longer distance connection than that with mobile handsets.

If the initial findings hold, it suggests that standard estimates for GSM network coverage may be higher (potentially much higher) for PAYG solar (and other machine-to-machine, intermittent communications) than normal voice and streaming data connections. A first-order analysis of the difference between convention estimates for network coverage (Figure 10 panel A) and based on the field observations indicates that coverage in Kenya is not confined to densely populated areas, and depending the local terrain and radio conditions, nearly all of the geographic extent of the country may be reachable. Improved modeling and systematic data collection could provide a new set of network coverage models for M2M applications that transcend the traditional boundaries of the networks for voice and text.

There are two important implications in the case where connectivity is stretched:

First, that connectivity-enabled PAYG systems may have more reach possible than previously thought. Without connectivity, other means of payment verification are needed to reach far-flung households with solar: scratch cards, unique codes, and communications shuttling. Research from GSMA suggests that circa 2015 60% of the off-grid people in Sub-Saharan Africa are covered by GSM networks, but our finding suggests this number may be much higher for the particular application case of PAYG systems.

Second, there may be opportunities to built new applications that make use of the M2M data transfer chip to send and receive additional data where there are low requirements for latency and/or bandwidth. For example, emails and text-based content could be sent and received, or, music and visual media that are cached locally (as opposed to streaming).
Figure S10: Panel A shows the expected reach of GSM mobile phone connectivity if the maximum tower reach is 35 km, based on the reported locations of the mobile phone towers and stations used to report data from the SHS. Each circle represents one tower and has high transparency (alpha = 0.1). Darker regions of color saturation are areas with overlap. Panel B shows the same set of towers, but with the reach of each tower based on the 90th percentile of distances between the towers and instances of SHS data transfer, using our estimates for the location of SHS that accounts for disparity in tower signal strength.
CONCLUSIONS AND NEXT STEPS
The reach of information technology into the energy system spans from century timescale global development efforts to real-time individual behavioral dynamics. We showed in Decentralized energy systems for clean electricity access (Chapter 1) that it is a unique moment in history with an opportunity to close a centuries-old access gap that has persisted since the initiation of utility electricity sales in the late 1800's. A key to closing the gap could be moving beyond the centralized grid model, expanding a new decentralized energy infrastructure network that distributes preconfigured systems built with scalable and modular generation and superefficient loads. While household systems are often referred to as “standalone,” taken in whole they are only isolated in terms of their electrical circuits. These systems rely on global infrastructure networks of distribution, manufacturing, service, ICT, and finance. But critically, the barrier to entry at the individual level can be lower than achieving a connection to the grid.

In order to reach scale, others have shown and we confirmed the critical role of financing to spread costs and risk over time for retail customers and the need for strong institutions that are well-suited to support markets for often fast-changing electronic goods. Expanding access and capabilities with ICT networks holds the promise to make advances on both fronts. In Off-grid power and connectivity (Chapter 2) and Quality Communication (Chapter 3) we mapped the supply chain for off-grid solar with a focus on PAYG systems and the Kenya market, and identified potential areas where institutional support could support off-grid solar access.

Finally in Off-grid solar energy services enabled and evaluated by information technology (Chapter 4) we used newly available remote monitoring data from PAYG systems to develop approaches for understanding the relationship between individuals and household energy technology. On the individual level we showed that a balance between reliability and quantity of service is experienced by users of the systems, and that half of the users actively manage their solar module, resulting in lower than expected electricity availability compared to those who leave it permanently mounted. For the fleet of decentralized energy systems we identified new metrics that could be used for benchmarking the economic and environmental performance of systems in real time.

Taken together, the findings offer insight into both the potential for acceleration of access to basic modern electricity services (lighting and power for ICT devices). There are also a range of critical issues that should inform an approach towards achieving the goals of universal access and climate stabilization that honors the agency and value of individuals who will be asked to participate in the challenge.

URBAN AND RURAL CONCERNS
It is now well known that many people without access to grid electricity are not the dispersed rural poor, but live in urban and peri-urban environments often literally under (or within sight) of power lines (17). In these and many other cases, a connection to the grid likely makes much more sense socially than household-scale systems in spite of similar levels of material affluence to the rural poor. Beyond the moral reasons for encouraging grid connections there are practical
considerations as well. For people facing the insecurity of high-density and often informal neighborhoods, the burden of active solar management to protect against theft is an additional cost in effort and results in lower service levels. The system we assessed in Chapter 4 has an architecture that is particularly forgiving to active management, but many others (and those that are widely sold as entry-level lamps to the poor) could result in 30-40% losses in available power. There are, however, good reasons people may like to have a battery backup to improve the reliability of basic lighting and communication services. In urban environments, superefficient appliances paired with battery backups that can be charged by the grid may offer superior reliability than an uncontrolled grid connection and lower costs than pico-solar (both monetary and the time it takes to protect against theft). The high value of reliability for basic lighting and communication means that a very unreliable grid connection may be less valued for human development than reliable low power systems. Combining with intermittent availability of high power services with a distributed system of rechargeable and local batteries in a stack could improve electrification benefits for the urban poor beyond what either a grid connection or a solar home system can provide.

There may also be value for those in outlying areas for accelerating adoption of backup basic power systems that are dual-powered by solar and the grid in high-density places. In our surveys with solar customers we found a large majority (90%) had heard about solar from someone they trust, usually a friend, before deciding to purchase. The social aspects of building demand through word-of-mouth along with urban-rural connections of family members and remittance, could be well matched with PAYG. With mobile payments, it would be possible as well to use the payment systems as a form of focused remittance. Urban use of backup power could lead to demand for solar in rural areas through those social connections, passing along with them the cache of urbanity as was the successful message in early roll out marketing of M-Pesa in Kenya, the now-ubiquitous mobile money platform (52).

**Reliability and the Value of Electricity**

A key theme of our findings was the way reliability of power was a key driver for the eventual energy service. People showed a preference for short-term reliability on a day-to-day basis and experienced far better reliability than what one would expect if the only goal was service quantity maximization. For people who moved their solar module, it was long-term reliability that was a concern (i.e., ensuring they have service now and into the future by keeping the system safe from thieves). While not revealing the motivations and underlying psychology of demand directly, our analysis showed the need and potential for using better reliability metrics than ex ante engineering estimates for assessing the value of off-grid power and continued improvements in understanding of the relationship between social and technological systems.

**Off Grid Power**

Widespread use of decentralized solar power beyond the margins and incorporated into the mainstream of strategies for electricity service in developing world would be a fundamental shift. While it would improve the equality in access it would not erase the gap between grid-connected (and usually more affluent) people and those with off-grid services, and there are important
questions that remain about whether adopting off-grid solar could slow or stall progress on widespread grid connections. Given the response to our survey when people were asked about preferences for expanded service (they would like brighter lights, more appliances, etc.) and trends in the joint development of income and appliance demand observed for grid-connected people (53), it stands to reason that decentralized energy systems should not blunt demand for increased service. It is possible, however, that investment in the systems could delay grid connection if the short term cash deficit often imposed by purchasing a solar home system imposes an unexpected constraint to connecting with the grid (e.g., there is a shift in cost structure for initiating a connection during the repayment period for a PAYG system that leads to a shift in preferences between solar and the grid). A more serious concern may arise in cases where policy pressure to reduce the cost of grid connections or expand service areas is reduced based on notions that decentralized power systems are sufficient. People with decentralized solar still remain on the margins of the grid.

AMPLIFICATION AND EQUITY

Two common threads in development interventions are questions concerning amplification and equity. Amplification is the concern that a technology may have unintended negative impacts on the community, by providing greater good to those with greater relative power or affluence—magnifying and adding to existing inequality in the society. These effects are well documented in other instances of ICT for development studies, e.g. M-PESA, lauded for its wide impact on Kenyan financing, is more likely to be held by those with more funds, slightly more male, better educated, and more literate (52).

An amplification concern for ICT enabled clean energy is that requiring different degrees of ICT access for participation will present new access barriers for the already disenfranchised. While access to mobile phones is nearly universal, it is not the case that mobile banking (or advanced ICT literacy) is as widespread. To the extent that people who are digitally literate tend to be more affluent, an amplification effect would occur if ICT approaches are a required step in accessing clean energy. We found in our study however that most (but not all) PAYG customers were able to understand the payment systems with little difficulty, thanks to both careful human interaction design and, in some cases we observed, the help from more digitally savvy family members (e.g., children or grandchildren of an elderly person who is uninterested in learning a new payment mechanism). Overall the vast majority (90%) reported no issues with payment.

However, there is still an outlay in up-front payment required for most PAYG SHS, e.g., about $30 in the case of M-KOPA—a prohibitive amount for many of the rural poor who may still distrust the quality or likely performance of the technology. This up front payment is in place as a proxy credit check and to reduce the likelihood of fraudulent purchases and makes sense from a business perspective in the absence of better information about credit risks for customers. People without the income to purchase an M-KOPA system may be able to purchase (usually for cash) a smaller scale pico-solar device, but the expected levelized cost of service is higher for smaller devices (a logarithmic relationship (2)), and thus the service reduction is on the order of the underlying income disparity amplified by the higher unit cost of service.
This amplification can occur within the supply chain as well. One of the retail solar business owners we spoke to in the course of research provides an example of how it requires particular skill and access to social and cyber networks to successfully operate and grow a business in the modern solar supply chain. He runs a successful distribution business in Kericho, and his two storefronts in town feature a range of household solar equipment, distributing goods offered by SunnyMoney (d.light and Greenlight Planet, among other brands), M-KOPA, Azuri (a scratchcard-based PAYG system), and others. Along with his wife, the accountant for the business, he lived for part of his adult life in England but came home mid-career to start a mobile phone distribution business. With the foundation of successful phone sales, he built a solar product line in response to growth in the market over 2012-2014.

Being successful for the business required first and foremost that he coordinate a network of sub-distributors who purchase (or receive on credit) cartons of products to sell on the street and shops in Kericho and the surrounding markets. Working through text messages and quick phone calls, he and his deputies coordinate this informal sales team. The other crucial element of success is good coordination with the large distributors and off-grid energy companies that provide products. He also got support from the GIZ EnDev program, for trainings of rural sales agents and providing startup funding for the sales network. These communications with global and national actors are often via email, on phone calls, or at in-person meetings in Nairobi (a day’s drive away). When we asked him what one of the best things would be to help his business, he expressed a surprising need: a support person to manage back office information and a laptop computer for the increasing range of electronic information he needed to manage. His current approach for information management and communication is to operate day-to-day through a smart phone with a data connection and spend several hours in a cybercafé once a week or so to manage larger emails and other tasks that are beyond the capabilities of his smart phone. He described increasingly difficult requirements for meeting the communication requirements of his growing number of national-level sellers and the support program, which required detailed accounting of how support funding is used via email, on spreadsheets. The example illustrates how a degree of sophistication with ICT for both “local” and “global” communication is vital for people like retail and regional distribution sellers who are important links in the supply chain, but also how insufficient ICT capabilities and capacity in periods of evolving needs can create friction for small but growing off-grid solar enterprises.

DATA AND SOCIETY

We demonstrated the value of data access for significantly improving the visibility into the dynamics of energy systems in operation (Chapter 4), while also tracing the networks of power that generate them through market and other structures (Chapter 2 and 3). There were also real concerns expressed by individuals in focus groups we ran about potential harms that could occur if privacy and confidentiality are breached in a personal data release. There are also concerns about dissemination from firms that gather data related to proprietary claims on mining value. Balancing the value of publicly available high resolution data (or verified aggregations and transformations of the data) with potential harm from breach or release to individuals and business interests is a critical task for information science in the coming century. This holds not
just for energy utility data but more broadly for business process and personal social data on the internet. The challenge calls for bringing together technology domain experts, social researchers, practitioners, and information security specialists in a research and implementation partnership.

**Towards a Theory of Energy Access**

The networks of power that enable grid connections are mirrored by the set of networks supporting off-grid energy. These intertwined global systems—electric power grids, transport networks, utilities and businesses, financial services, multinational manufacturing, governments, and information technology—have unique and often locally heterogeneous characteristics of access and equality in power. People who sit at the confluence of power across networks have amplified and broader access to the human needs services that hard and soft infrastructure deliver, and the structural geographic, political, and economic inequality that emerges is a key driver for the inequality in service that we observe between those with and without access to electricity. These global-scale industrial systems both rely on and heavily tax the natural resource and ecological networks of our planet. Thus a critical question presents itself in the emergence of off-grid power systems: can these manufactured devices that are linked with global networks of trade, capital, and governance effectively address the very excesses in consumption and unequal access to resources that emerge from the industrial system they rely on? Does the addition of information technology as a supporting element democratize clean energy or lead to more consolidation and control?

The early evidence and a hopeful view on the near future point to the potential to improve the equality and environmental impact the overall energy system with decentralized power. The opportunity with household solar is to improve but not close the gap in service and emissions intensity between those with and without grid power. The diffuse nature of mobile phone and retail sales networks means many more people are within reach than those to power lines, and having essentially portable and relatively reliable household energy systems could match the itinerant and often uncertain living situations of the poor better than buying in to a fixed infrastructure system with uncertain reliability. There are also field-leveling features of PAYG energy systems when there is a blanket offer across regions, with implicit urban-to-rural subsidies in pricing from no differences in cost depending on the remoteness of a sales point, mirroring but not equaling subsidies that are often implicit in the cost structure of large-scale grids.

As electricity systems both on- and off-grid expand in reach and capabilities with ICT as a catalyst there is a need for new theories of energy access that reflect the diversity in practice and experience we observe. It is pithy and accurate to say individuals and societies don’t want kilowatt-hours and instead it is the energy service they receive, but up to now it has been difficult to meter beyond quantities of energy consumed. To guide effective global action on climate and inequality there is a need and opportunity to put emerging information resources to use in the public interest. Increased visibility and availability of data from energy systems, grounded with the context of use and appropriately governed, could better inform and guide efforts of policy...
and enterprise, contributing to transformation of a legacy system of centralized power generation with fuel-based lighting filling the gaps to an inclusive system of decentralized clean power.

**POLICY AGENDA**

The findings of my work suggest opportunities for near-term action in support of improved energy access and longer-term effort to better understand and shape the energy system.

- Energy access measurement should recognize the phenomenon of energy technology stacking and use real-time data and other business process data to augment and improve the accuracy of tracking progress. While many examples exist today of service being defined by resource ‘access’ metrics such as water pumps per 1,000 of population, or energy generation capacity per citizen, the evolving IT-rich world has made these aggregate measures of actual service obsolete. New modes of information feedback and communication now permit a far more granular and nuanced assessment process for the costs and quality of services provided, and to whom they are available.

- Add new metrics for reliability and other dimensions of service beyond quantity to energy system tracking. Measuring and benchmarking conditional reliability has the potential to move beyond system-level, annual metrics to those that consider the provisional value based on the time of day, predictability, and loads that experience (un)reliable power. While this reliability is itself a key feature of the successful commercial markets, its communication is also a key element of the product-service pipeline and is one that is often overlooked or ignored entirely.

- Cultivate energy data access exchanges and partnerships between the public and private sector. There is a high potential value for public access to data for monitoring the results of technology system development, and a discursive and public process could help accelerate progress by making available the best available data resources to guide efforts fighting poverty and climate change.

- Institutions and organizations engaged in the market with ICT-based interventions could identify opportunities to smooth ICT-based inequality in the market. Better information about consumer credit (either for individuals or for general populations of customers) could reduce the potential amplification of inequality through decentralized power systems by reducing the up-front cost barrier to PAYG SHS. Training and support for small enterprises of sales and support could lead to more robust and locally-rooted supply chains for energy as well.
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