Sustainable Humanity, Sustainable Nature: Our Responsibility
Pontifical Academy of Sciences, Extra Series 41, Vatican City 2014
Pontifical Academy of Social Sciences, Acta 19, Vatican City 2014
www.pas.va/content/dam/accademia/pdf/es41/es41-kammen.pdf

# Energy for Sustainable and Equitable Development

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## Abstract

With 1.4 billion people lacking electricity to light their homes and provide other basic services, or to conduct business, all of humanity (and particularly the poor) are in need of a decarbonized energy system that can close the energy access gap and protect the global climate system. With particular focus on addressing the energy needs of the underserved, we present an analytical framework informed by historical trends and contemporary technological, social, and institutional conditions that clarifies the heterogeneous continuum of centralized on-grid electricity, autonomous mini- or community grids, and distributed, individual energy services. We find that the current day is a unique moment of innovation in decentralized energy networks based on super-efficient end-use technology and low-cost photovoltaics, supported by rapidly spreading information technology, particularly mobile phones. Collectively these disruptive technology systems could rapidly increase energy access, contributing to meeting the Millennium Development Goals for quality of life, while simultaneously driving action towards low-carbon, Earth-sustaining, energy systems.

## Introduction: Global Energy Challenges

Two critically important 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, providing services that unlock economic and social free-

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doms [3], pollution from the energy sector is the primary driver of locally and globally disruptive 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 is both a critical task for improving the quality of life and enhancing human development opportunities [4, 5]. However the notion of universal electrification is a key point of contention for negotiations on climate change mitigation [6, 7]. This tension between energy services and increasing emissions exists because of the dominant paradigm for electrification in the industrializing world, i.e. through centrally planned and currently carbon-intensive power systems [8]. Despite its undisputed value, without significant changes to these trends, a billion people are projected to remain without access in 2030, with the majority in Sub Saharan Africa and significant numbers in developing Asia [9]. Eighty percent of those projected to remain in deprivation live in rural areas, where the lack of modern infrastructure and services directly result in low resilience to the potentially catastrophic impacts of climate change, such as drought, losses in agricultural productivity, and extreme events [1, 2].

To clarify the potential of technological, political, and market mechanisms to sustainably addressing household-level and global energy needs, we present a historical and conceptual framework to evaluate the opportunities to manage energy and information resources over vastly different scales of network services. Focusing on electricity access for the poor and unempowered we begin by (1) exploring the links between access to electricity and human development; (2) considering the historical trajectory of electricity technology systems and (3) describing an emerging continuum of electricity technology options available today.

Our synthesis of the available data moves towards an integrated theory for understanding the dynamics of on- and off-grid energy systems in the Anthropocene [10-12] based on emerging understandings of network dynamics [13]. The implications for power system development on- and off-grid can contribute to achieving universal access using strategies that improve *both* human development and climate impacts from the energy sector through the effective support of networks for energy access, including novel approaches that leverage ubiquitous information technology connectivity. With better frameworks for understanding the complex systems that are the foundation for energy access both private and public sector agents can better target their efforts.

## Energy and Human Development

Thus far, progress towards eradicating energy poverty has been insufficient in scale and pace. Unserved populations still primarily rely on low-efficiency open flames for lighting [14] that is often inadequate [14], incurring substantial economic costs [15] and increased health [16] and safety risks [17]. Greenhouse gas emissions from fuel-based lighting are significant [14], particularly in light of recent findings on black carbon from wick lamps [18]. The off-grid poor devote also devote large amounts of time and financial resources to charge mobile phones [19, 20], which are used by 72% of people in low-to-middle income countries, a twenty-fold increase since 2000 [21]. Mobile phones have become 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 access to information [22].

Access to electricity is linked with improvements in human development including productivity, health and safety, gender equality, and education [2, 16, 17, 19, 23, 24]. Much of the research broadly describing quality of life and electrification, stems from the pioneering insights of Goldemberg, Johansson, Reddy and Williams [25] 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) [26]. 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 [26-30].

Figure 1 shows consumption-based relationships in the spirit previous work along with a 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 a power law decline in returns to human development as they increase, access is first-order linear predictor of HDI along with an important set of selected MDG over its full range. This is consistent with an aggregate view of household-level diminishing returns on energy consumption, where the first 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. The underlying relationship between development and electricity consumption cannot be extricated simply from macro data. There are numerous complex socioeconomic factors that can contribute to a high consumption per capita, including industrial activity, geography, and political relationships [27, 28, 30]. Although it is difficult to determine causality [29, 31-33], there is sufficient case study data

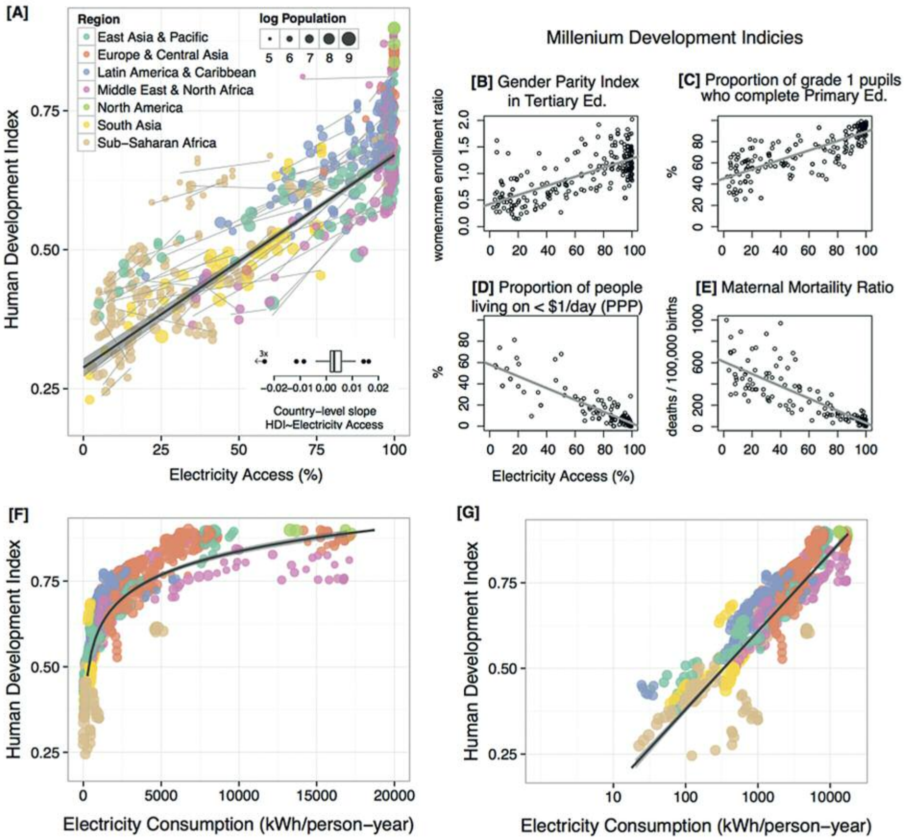


**Figure 1.** The relationship between access to electricity and human development ([A] HDI, [B]-[E] Selected Millennium Development Indices, 2000-2010) and between electricity consumption and HDI similar to the relationship originally suggested by Goldemberg, Johansson, Reddy and Williams [25] ([F] on a continuous abscissa, [G] with a logarithmic abscissa). All the data are on a country level. In [A] country level regressions along with a full regression are shown for the relationship with HDI, and the distributions in slopes on a country level indicates the global relationship holds within countries over time (typically). The $R^2$ values for the full-sample linear regression are [A] 0.65, [B] 0.52, [C] 0.66, [D] 0.72, [E] 0.69, and [F]/[G] 0.81 (same relationship on different axis scales).

[19, 23, 34] to provide a strong argument that electricity access is a necessary, but not sufficient, condition for improving human development.

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 [1] and Human Development Reports [35]. 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 [35] 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 [35]. A direct measure of electricity access – in terms of the fraction of households with modern energy – is currently missing from official development tracking but has been proposed for a 2015 update to the Millennium Development Goals (MDG) [20] and there is a proposed *Global Tracking Framework* for energy access in a pilot testing process that could support explicit access goals [2].

## Networks of Power and Technology

The expansion of energy 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* [36], this can be understood using the concept of the "reverse salient" as a bottleneck for development). In the case of electric utilities, the genesis of utility networks was in 1882 with the Pearl Street Station in New York City. These were greatly enabled by technology innovation across supply and demand technologies (including dynamo generators, AC transmission and distribution, and efficient lighting and motors that occurred in the late 1800s and early 1900s), and catalyzed by the critical development of a new 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 [37].

Branching out from the early-adopting coastal hubs of New York, Paris, and London, multinational private enterprise opportunistically followed existing links of trade and capital to quickly electrify the world's cities and factories, using mainly standalone power stations and minigrids. 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 disconnected urban and industrial users with concentrated demand and ability to pay for electric service that combined to create both smaller and higher return investments in transmission and distribution infrastructure per customer. 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. By the 1930s-40s, the 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 [37]. By 1930, electricity had transformed the lives of many city dwellers but rural populations remained in the dark [36].

## Rural Electrification

The Tennessee Valley Authority (TVA) is a classic and instructive example of early efforts public institutions took to drive development of electricity networks in areas of deprivation that were neglected by the private sector. Part of the broader "New Deal" program of United States government infrastructure projects and financial reform in the 1930s, it featured many elements that are present in current-day debates around rural electrification. The TVA was sold 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) and also on the basis of providing populist "Electricity for All" (see SOM) while taming the capricious Tennessee River to make it navigable and less disruptive with a series of large hydroelectric dams [41]. In the context of linked networks, it was the river that provided a critical natural support structure for the project, aggregating fuel supply (water with elevation change) and population density along its reach. Although 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 [41], during the development of the TVA, the project encountered opposition and criticism from many perspectives [42]. 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 [43]. Further objections arose from existing racial and socioeconomic disparities in the region that were magnified in the allocation of jobs and services in the Valley [44]. 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 [45].

Similar rural electrification dynamics continually play out as power grids expand in the developing world, with combinations of private and public initiative, issues of equity in development, and the inevitable localized negative impacts from expanding transmission networks and power stations, such as loss of land to eminent domain, environmental degradation, and other issues. While power reached the cities and industry of the developing world in the early 1900s around the same time as it reached cities in the industrialized world [46], rural (and poor urban area) electrification has significantly lagged industrialized countries. The current electrification rate in developing countries, as classified by the International Energy Agency, is 76.5%, as compared to OECD nations with an electrification rate of 99.9% [47].

A key challenge in rural electrification efforts is the cost of building the distribution system to go the "last mile". 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 have an even lower ability to pay for the service (or buy appliances that result in higher demand) [48]. In the context of typical annual household expenditures (approximately $1000 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, it is clear that it is often financially undesirable for system operators to expand electricity services to the rural poor, who may not 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 the often-polemic, multinationally funded 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, DRC, and Rwanda, and other related initiatives [49]. These large-scale activities, while incredibly important for national growth, are not without their drawbacks, reflecting the previously learned lessons of the TVA. The expansion of hydroelectric generation in Ethiopia, for example, has been a point of contention for academics, non-profit advocacy groups, and even regional governments. Much of the discussion today focuses on many of the same issues as with the TVA, including displacement of populations [50], disproportionate impacts on the poor and marginalized people [51], and political tension [52].

The development of transmission infrastructure to create regional interconnected networks, such as the East African Power Pool (EAPP), illustrates other common drivers for transmission network expansion today: the desire for a greater stability, expanded service provision, reduced locational marginal costs, and opportunities for trade and international collaboration. In many cases, this expansion is not only driven by, but also acts as a driver of the previously mentioned extensive energy resource development projects. Regional interconnection is not without its faults however, and the technical difficulties of interconnecting large-scale power systems can be complex, especially when member states operated under independent grid codes in the past. Furthermore, because institutional and administrative features can vary from country to country, the technical and operational attributes of initially independent national systems can be quite disparate. This adds to the challenge of successful interconnection when it is done through HVAC transmission infrastructure, where synchronicity of systems is key to ensure reliable service. In such systems, disturbances in one area can rapidly degrade service provision across the whole network [54, 55].

## Energy Poverty Today

In spite of rapid expansion driven initially by the private sector and later by public institutions, our analysis of the archival record in Figure 2 show that since the initiation of centralized electricity, 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

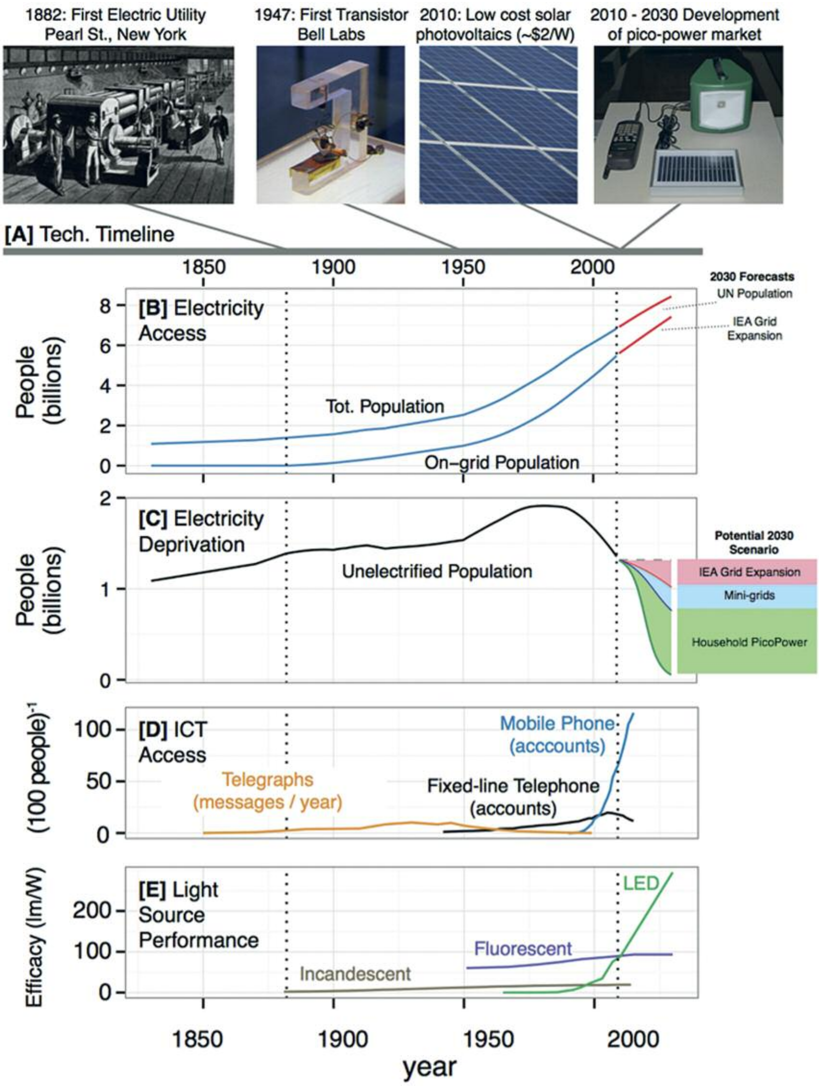


**Figure 2.** Two centuries of historical trends and a potential future scenario from 1830 to 2030 for electricity access in the context of technology and supporting network events and trends. [A] The technology timeline shows watershed moments of innovation and market paradigm shifts. Panels [B] and [C] show the population with access to electricity over the time period, with [C] including 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.

roughly paced global population growth since 1900. About 1.4 billion people in 2013 [2] are completely off-grid, and many ostensibly connected people in the developing world experience significant outages accumulating to 20-200+ days a year [56]. The pervasive "energy isolation" people experience, in the context of grid-based electricity, stems from being remote in multiple dimensions:

- Geographically remote: Long transmission distances, diffuse population densities, and difficult terrain quality restrict grid extension to many rural areas due to high marginal cost of connection compared to expected usage [23].
- Economically remote: The rural and urban poor do not consume large quantities of electricity due to budgetary restrictions and often struggle to pay connection fees to nearby grid infrastructure or procure household wiring and appliances [57]. Many households and businesses in "electrified" areas lack access, even directly beneath power lines. Principle-agent market failure may contribute to this phenomenon for renters.
- Politically remote: 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 [58] [23]. People without property rights may lack the stability to justify investments in fixed infrastructure, or permission from central authority to do so.

## Off-grid Energy Access Technology Continuum

A contemporary continuum of off- and micro-grid electricity systems does not require the same supporting networks as centralized power generation and can overcome energy isolation barriers. The process of network expansion for decentralized power is fundamentally different from electricity grids. Where electricity grids require installation of capital-intense fixed infrastructure – plants and relatively large loads connected by transmission and distribution followed by infill and rural extension – the decentralized power network is more diffuse. There are still important hubs like factories in Southeast Asia where a majority of components and integrated systems are produced, but these are connected to end users by global supply chains and knowledge networks instead of fixed physical infrastructure.

Dynamo generators and arc lighting catalyzed the market for electric utilities and it is a range of semiconductors (stemming from the discovery of the transistor noted in Figure 2) that enable 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 [59] (e.g., see Figure 2), DC televisions [60], refrigeration [61], fans [62], and ICT [63] (a "superefficiency trend") that enable decentralized power and appliance systems to compete with legacy equipment on a cost for energy service basis.

With these technological cornerstones, aid organizations, governments, academia, and the private sector are developing and supporting a wide range approaches to serve the needs of the poor, including pico-lighting [14], solar home systems, and community-scale micro- and mini-grids [2, 4]. In many cases, preconfigured systems are sold in market-based structures, rather than involving the establishment of geographically tied institutions [64]. Figure 3 shows the range of costs for decentralized power across several orders of magnitude in scale and shows a caricature of the typical temporal cost structure for each. We observe a power-law inverse relationship between the unit cost and scale of electricity supply technology from pico-power to gigawatt grids.

The off-grid poor reveal a high value is 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 2A. Given the cost and service level that fuel-based lighting and fee-based mobile phone charging provide as a baseline, simply shifting 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) [65]. In fact, many of the off-grid poor have already switched to LED lighting, but often to low-quality products that consume relatively expensive dry-cell batteries (with effective electricity prices of $100's per kWh). Although such technologies represent a step forward in the quality and convenience of lighting, they maintain a high cost to the consumer and result in significant electronic and battery waste streams in countries that are poorly equipped to manage them [66, 67]. This waste stream can contribute to significant environmental degradation, human health impacts, and other social concerns [67-70].

The transformative nature of superefficient lighting is also highlighted in Panel C 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 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 [65].

Meeting peoples' basic lighting and communication needs is an important first step on the "modern electricity ladder". This can be easily accomplished without necessarily increasing overall energy consumption if

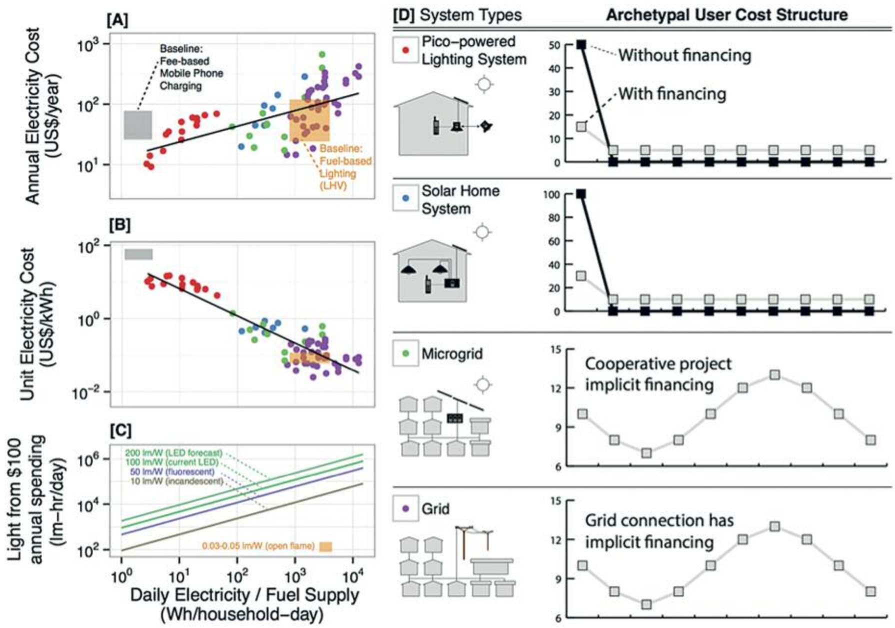


**Figure 3.** The total annual [A] and unit cost [B] of electricity over a range of daily supply levels and technology types. The incumbent energy access options (fuel-based lighting and fee-based mobile phone charging) are included for reference, with fuel-based lighting expressed in terms of the lower heating value of a range for typical fuel consumption [15] and prices paid for fuel [71] with ±50% bounds around the price to account for spatial and temporal variation. Panel [C] shows the implications of superefficient lighting for getting energy service 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 the scale of the system) based on the regression in panel [B]. For reference a range of service provided by fuel based lighting is also shown as an orange rectangle, with bounds defined by uncertainty in the price of fuel (from USD 0.75 to 1.25) and the efficacy of the flame (0.03 to 0.05 lm/W). In [D], for each electricity technology type, we show a pictogram of the system arrangement and an archetypal cost structure for end users. The cost structures illustrate how the availability of financing. The data sources for the cost and performance of technology are described in the Supplementary Material.

| Technology | Generation Capacity (Watts) | Services Available | Energy Isolation Barriers |
|---|---|---|---|
| Incumbent technology bundle: Fuel Based Lighting, Dry cell batteries, Fee-based mobile phone charging | N/A | Lighting, Radio communication reception, Two-way mobile communication | **Economic:** Very Low barrier. Day to day payments for increments of energy<br>**Geographic:** Low barrier. Requires distribution to remote areas through normal supply chains with some markup.<br>**Political:** Low barrier. Gov't and institutions can support market or hinder depending on policies. |
| Pico Power Systems | 0.1 – 10 | Lighting, Radio communication reception, Two-way mobile communication (Note: basically the same as incumbent bundle) | **Economic:** Low barrier. Market-based dissemination. Retail cost USD 10-100<br>**Geographic:** Low barrier. Requires distribution to remote areas.<br>**Political:** Low barrier. Gov't and institutions can support market or hinder depending on policies. |
| Solar Home Systems | $10 - 10^3$ | Same as above plus television, fans, additional lighting and communication, limited motive and heat power. | **Economic:** Medium barrier. Market-based dissemination. Retail cost USD 75-1,000<br>**Geographic:** Low barrier. Requires distribution to remote areas.<br>**Political:** Low barrier. Gov't and institutions can support market or hinder depending on policies. |
| Microgrid | $10^3 - 10^6$ | Same as above with opportunity for community-based service with higher power requirements e.g. water pumping or grain milling | **Economic:** Medium-high barrier. Requires financing or investment aggregation for large capital outlay but offers relatively low marginal cost electricity to users.<br>**Geographic:** Medium barrier. Requires critical density of population<br>**Political:** Medium barrier. Requires community support and local political decisions. |
| Regional Grid | $10^6 - 10^9$ | Depending on the quality of connection, same as above up to a full range of electric power appliances, commercial and industrial applications. | **Economic:** Medium to high barrier. Often high initial connection costs, but low cost power after connection. (Cost of power lines)<br>**Geographic:** High barrier. Requires nearby transmission and distribution infrastructure.<br>**Political:** High barrier. Depends on ministerial and departmental decisions about extension. |

**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.

efficient end-uses are combined with low-carbon generation [65] while still leading to substantial benefits in household health, education, and poverty reduction [19, 72]. Beyond basic needs there is a wide range of service provided depending on the power level, reliability, scarcity, and power quality along with demand-side efficiency and appliance access. There will be significant rebound effects due to decreased unit costs for better quality energy services when moving up the "electricity ladder" as people fulfill unmet needs by re-optimizing in the context of new technology options [73], but given the inefficiency of fuel-based lighting, a rebound equivalent to roughly 500 times the baseline service level is required before the environmental gains from switching to modern energy systems are negated [65].

## Institutional Support for Off-grid Power

Filling the gaps left by grid expansion, decentralized rural electrification with off-grid power has been a consistent feature of development efforts with varied levels of commitment and success on the part of local private sector, government, and multinational development agency involvement. While home-scale solar electric systems have been possible and were described as early as 1959 [74] the cost was prohibitively expensive until at least the 1970s when the "first wave" of solar development efforts focused on rural areas of Sub-Saharan Africa and Asia. During that time it was public institutions that were leading rural electrification efforts through the grid and much of the effort towards off-grid solar was also directed by governments and development institutions. These early programs developed an important knowledge base for rural off-grid energy development and also lead to some cautionary tales.

One example of national rural energy access efforts is the National Electrification Program (NEP) in South Africa, which formed as part of the Reconstruction and Development Program after the first democratic elections in 1994 [75]. The program was successful in many regards; access to electricity increased from less than 35% to over 75% in less than a decade [76]. However, many have critiqued the implementation and efficiency of the off-grid program components, i.e. primarily the fee-for-service solar electrification program, pointing to significant wasted resources and structural inadequacies of the institutions that were developed to manage the system [76, 77]. Although the goals of the program was incredibly ambitious, and the government attempted to employ the private sector in a large degree, only 50,000 solar home systems have been installed so far, and an unknown quantity (assumed to be quite substantial) are no longer operational. The primary causes are believed to have been a lack of political will and vision, disruption of capital subsidies by the central government, nonpayment of fees and poor tariff collection by concessionaries, and the perception by the users that systems are temporary or inferior due to the marketing of the program [23, 77].

In South and Southeast Asia, off-grid electrification efforts have also been mixed, although a number of successful initiatives have shed light on effective best practices. In all cases, government involvement through the setting of an enabling policy framework has been key (such as VAT exemptions, microcredit systems, subsidies, and income tax exemptions), and in the majority, a large level of initial subsidies was required for growth and expansion [23, 78]. However, both Bangladesh and Sri Lanka have demonstrated success through market-based approaches, using public-private partnerships, dedicated government agencies, improved access to capital and grant mechanisms, and product standardization practices [23]. Grameen Shakti, which has been one of the primary private-sector actors in the off-grid space in Bangladesh, has benefited over 3.5 million people with their efforts, and have achieved success in tariff payback and service/maintenance for their systems, in part, by using micro-credit finance, locally manufactured system components, and the development of Grameen Technology Centers [78, 79].

## The System Dynamics of Energy Access

Understanding the dynamics of energy markets and peoples' interactions with the underlying technology systems is a critical goal for effectively addressing climate issues and energy deprivation. As modern on- and off-grid energy systems evolve in the context of their supporting institutions and information technology networks there is a need for transdisciplinary "theories" of energy access that can catalyze an acceleration of clean energy development that mitigates climate change and alleviates energy poverty.

One promising approach to a theory of energy access that combines technology and social systems is through a conceptual framework of linked and interdependent networks, as is caricatured in Figure 4. The figure shows how people are connected with primary sources of energy – natural forces like the sun and wind along with fossil fuel – through complex and material and energy transportation networks. The interface with users (e.g. solar LED lanterns, metered grid electricity connections and mobile phones) are often the iconic element but are closely linked and dependent on global physical infrastructure. In turn, those critical networks of physical infrastructure, and their operation, are supported by important information networks of policy, social interaction, economic exchange, and knowledge.

Network theory has been applied in isolation to many of the components of the energy-information nexus we detail here, and in a very preliminary way to the interconnected systems that we identify as supporting energy access including the development and growth of national power grids [80], electricity grid failure rates in North America [81], assessments of risks to, and vulnerability of, critical infrastructure [80, 82], the growth and emergence of the World Wide Web [83], the formation of policy stakeholder interaction networks [84], the network structures of water policy [85], the spread and scaling of hardline [86] and wireless telecommunications networks [87], financial decline and global economic networks [88] and the management of complex supply chains [89, 90]. Much more work is needed in this area, and in how best to integrate behavioral and consumer preferences in building functioning and profitable 'networks of service' for

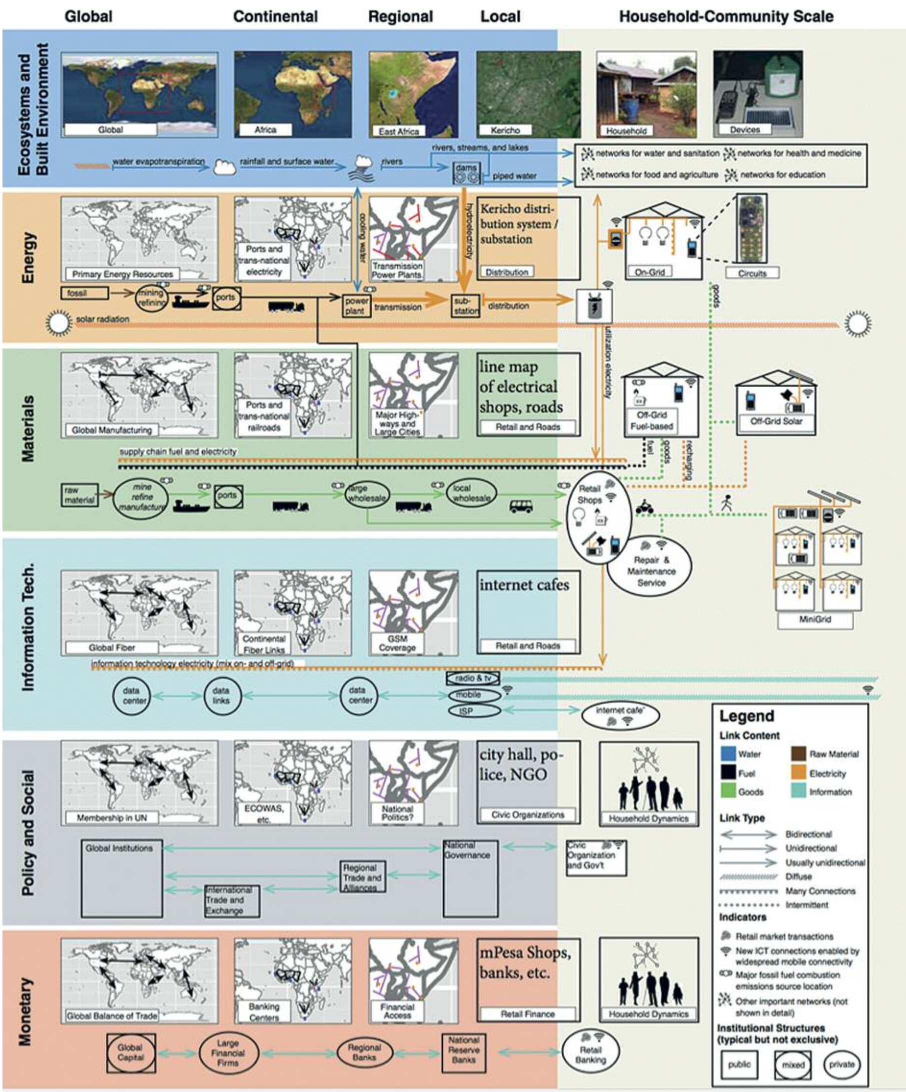


**Figure 4.** Multiscale, linked physical and information networks for energy access. This caricature zooms from global scale to a focus on households outside Kericho, Kenya but is meant to be representative of the dynamics for many other off-grid locations. [Note to editor: This is an evolving version of this figure. The maps shown here have dummy data but will be replaced with maps that have the best available data from current-day to map networks at these scales. We are aware of sources for these data and have access].

new energy customers. To date, no comprehensive analysis exists of the interconnections between these complex networks in the context of energy access on a global scale.

Linking diverse networks of physical materials, energy, and information with varied and uncertain structure is a scientific and engineering challenge that could lead to meaningful insights on how to more effectively manage complex technology networks in the Anthropocene [13, 91]. The concept of entropy – fundamentally a measure of order and uncertainty – may prove to be useful for linking networks since many of the underlying flows and processes can be reformulated in entropic terms. Thermodynamic and statistical entropy are well understood and documented for energy and material systems. Information and energy are physically coupled concepts and typically it is through the concept of entropy that they are related, using Landauer's principle that predicts the minimum energy associated with information is related to kT*ln2*, which has been verified for simple systems of molecules [92]. Similarly, the flow of money can be reformulated as information with a particular amount of uncertainty associated with it. In the 'thermo-economist' perspective statistical mechanics is used to formulate the flow of money and its distribution in the economy [93].

In each of the systems that comprise the network for energy access there is a tendency towards maximum entropy, but the goals of individuals and firms is often countervailing. People would prefer to minimize entropy locally (i.e., have more control over resources in the future and more certainty about future outcomes) by aggregating low-entropy resources – money, reliable energy network connections, durable technology systems, and stable social relationships. This fundamental tension in the context of agents embedded in networks of geography, technology, and information could be the core of a useful bottom-up theory for behavior in energy access networks.

The quest for certainty as a fundamental driver for behavior is an old idea [94] that takes on new meaning in the context of energy access networks. By framing behavior in terms of embedded agents applying Bayesian decision making – combining past experience with new information in the context of their expectations about the future and position in the broader network – all to minimize entropy (gain certainty), it is possible to explain a number of emergent phenomena that have been shown in other work to be important drivers in global networks. Agents who minimize entropy will have different tolerances for risk and future benefits depending on the stability of their position, which leads to future discounting and the concept of demand curves in the rational choice economic model. What seem to be unreasonably high future discount rates have been observed for a range of energy efficiency decisions and are often described as contributing elements to an energy efficiency gap [95], but could emerge from short-term constraints on cashflow (i.e., low entropy resources) and a quite reasonable preference to maintain low entropy through keeping cash rather than trading for future energy services. We also would expect diminishing returns from energy and information as people prioritize high-value (entropy minimizing) services like basic lighting (to reduce uncertainty about ones surroundings) and information technology (reducing uncertainty about the world in general), followed by less-important service. These diminishing returns are manifested in the relationship between human development and energy consumption observed by Goldemberg, where steep initial gains are seen during energy consumption growth, but few gains after.

Our observations of the structure and dynamics for energy access networks, characterized in Figure 4, reveal several patterns for understanding how decentralized systems can play an important role in meeting energy access and climate goals and help overcome the barriers people face to reliable access to electricity through the grid.

Resilience – in this context the probability and certainty of energy service "uptime" – is an important part of the value of power networks. The structure of electricity transmission and distribution systems typically includes some inherent resilience to random failures of particular components because they are "scale-free" networks that have a structure with hubs of local importance and strength (Chassin, 2005), (Callaway, 2000). However, in much of the developing world, the power grid (transmission and distribution electricity links in the diagram) is quite unstable with long periods of brownouts (low voltage) or blackout [96-99]. On the other hand, a well-functioning off-grid power system may provide more reliable power, albeit at lower power levels. Conceptually, off-grid solar power is connected to a universal and stable hub for power transmission: solar radiation. While solar power is subject to diurnal and seasonal patterns in availability and the vagaries of weather it is not subject to the kind of random failure that afflicts complex electricity networks. Energy storage systems (batteries) are used to improve the reliability of solar power and it is also possible to add local resilience to grid connections with decentralized storage. A common but overlooked source of resilience is the batteries in a mobile phones and other devices that make them portable and also allow for decoupling from unreliable power availability, up to a point. The resilience of decentralized power systems may also be an important contributor to community resilience in the face of natural and unnatural disasters like large storms and civil conflict that can disrupt large-scale networks.

Decoupling end-user service from fixed geographic positions is another feature of some decentralized power networks, particularly pico-power devices, which are more flexible in their arrangement and relocation than grid-based power connections. For people who live in places that are only accessible on foot, it is not tenable to expect extension of an energy network that requires the movement of goods over roads. Additionally, many people – particularly the very poor – live in itinerant or temporary housing often with uncertain or nonexistent ownership. It simply may not make sense for some people who are off-grid to invest heavily in fixed or difficult-to-move infrastructure. Where fuel-based lighting was the only viable option for those particular network conditions before, there are now clean energy options that meet the same constraints but with better service.

Eliminating fuel-based lighting in favor of the grid or off-grid power serves an important public health need by shifting emissions associated with energy use and appliance manufacturing from inside the household where particulate matter and other pollutants are concentrated where people live (Lam, 2012) to factories and power plants that typically have better emissions profiles and dispersal. The quantity of emissions is also reduced; pico-power systems have very favorable life-cycle energy performance compared to fuel-based lighting (Alstone, 2013).

## Catalyzing Off-Grid Power

While off-grid power systems have several inherent advantages – network resilience, flexibility, and tangible environmental and health benefits among others – there are important barriers to overcome as well. Decentralized energy systems are increasingly distributed through market-based systems, with much of the investment risk often borne by diffuse end-users who, compared to the developers of central power grids, currently lack the ability and incentives to engage directly with the global market. While they already pay as much or more for lower quantity of energy service (see Figure 3a), support is vital to mitigate risks throughout the supply chain with financing, product quality assurance, maintenance and support networks, and robust networks for exchange of knowledge and expertise [24]. Creating resilient and lasting networks for off-grid energy may not require building new power lines but relies instead on building strength and connections in the range of supporting networks highlighted in Figure 4, from supply chains to financing.

The private sector drives much of the development in the off-grid power market, as was the case for early grid-based power systems. Because there is no dedicated infrastructure required for off-grid power supply chains there is no natural spatial monopoly (as there is with on-grid power), allowing a range of private sector initiatives to coexist and compete for potential customers. Currently there is a wide range of business models and technology designs being tested and deployed, without clear indications that one particular technology and institutional structure is dominant (DGBA, 2012). The compelling technical and economic attributes of super-efficient end-uses and inexpensive solar charging drive the market, but institutional support is required to correct market failures around missing information and connections.

In response, global institutions that are often oriented towards supporting centralized physical infrastructure projects are refocusing to also provide targeted support for decentralized initiatives that can fill in the glaring gaps in service for the energy isolated poor, as can be seen in the efforts and projects of the Sustainable Energy For All Initiative of the UN [100], the recent revision to the World Bank's Energy Strategy [101], and President Obama's Power Africa initiative [102]. The transnational and multi-dimensional nature of off-grid energy access networks requires these new institutional responses to have different structures and activities from large-scale development efforts (e.g., financing or planning large power generation and transmission projects).

The Lighting Global project is an example of new institutional efforts to support and transform markets for off-grid power. Funded through the World Bank and IFC, along with the regional Lighting Africa and Lighting Asia programs, it supports markets for pico power energy systems with a range of information and educational interventions and through creating and strengthening links in the supply chain and supporting networks of finance. A key effort of the program is building a Global quality assurance framework that integrates standardized third-party testing, a set of minimum quality standards for buyer protection, and standardized ways of communicating positive test results to the broader market. By reducing uncertainty about product quality and performance the test program enables national governments, buyers, and potential financers in the market to regulate, choose, and support products with better knowledge about the likely quality. The program creates new links in supply chains with business-to-business matchmaking between parties that have passed a basic ethical and financial screening, and helps actors in the supply chain access financing.

## Information Technology and Clean Energy Deployment

The rapid emergence of global (decentralized) wireless communication networks and widespread access in the developing world [21] is a new and important support system for decentralized energy. Not only are mobile phones an important and highly valued source of electricity demand (as the radio was for early electric grids), but they also provide a new platform for finance and connectivity to support markets for pico-lighting and solar home systems. Targeted and well-designed "killer applications" of information technology hold the promise to accelerate the market for off-grid power and increase energy access for the global poor. The rapid expansion of decentralized mobile communication compared to fixed line phones (see Figure 2) is indicative of the potential for decentralized small-scale power systems to rapidly expand compared to fixed power systems.

Pay-as-you-go (PAYG) household and minigrid systems that use combinations of mobile banking, financing, and user outreach can make decentralized power accessible to people who are cash poor but are acclimatized to gathering small sums of money for ongoing energy costs [103], by making the payment stream for off-grid power more similar to the typical expenditures for traditional fossil or biomass fuels being replaced (and to ongoing costs for grid power). Financing clean energy fits peoples' ability and willingness to pay in the context of uncertainty and deprivation [105]. PAYG systems typically rely on mobile phones as a platform for making payments (or verifying the transfer of money) and some include a cut-off switch in the system hardware that prevents use when fees or loan payments have not been completed [106]. This ICT add-on to off-grid power hardware transforms decentralized energy systems into "energy as a service", rather than a durable goods purchase.

ICT is also critical feature for supporting the supply chains and maintenance networks that connect consumers with producers. Supply chain management and intra-chain information sharing and payments are important features of energy access networks much as they are for many other products [108-110]. 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 picopower deployment (DGBA, 2012).

Remote monitoring and analytics of off-grid power systems can be enabled when there are systems for collecting and transmitting system health and performance through ICT channels. Effective monitoring and maintenance is a common barrier across all decentralized modern energy systems, whether solar home systems, lighting, or improved stoves, especially in regions where technical capacity levels are low, and in the early period of diffusion 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 [104, 107].

As ICT is integrated throughout the energy system on- and off-grid there will be new opportunities and challenges around data management and control. With access to large-scale decentralized energy data across a range of network scales it may be possible for regulatory institutions to better protect and support consumers and for academics and scholars to test theories of socio-technical network dynamics (Barabási, 2009). "Big Data" is a potential microscope for investigating the society in which it is embedded but only to the extent it is available and rigorously analyzed. The status quo, however, is for data to be protected and mined by the private sector system integrators, who may extract different value from the data (e.g., by encouraging repeat customers or improving their competitive position with product design improvements). Both uses of the data are important but are in tension because strategic private-sector use creates more value for system integrators when data are scarce and not globally shared. There may be reduced incentive to include data collection components in off-grid energy systems without the incentives related to extracting value from the data before it is made public. Ownership of distributed energy usage data generated by systems that are owned by dispersed global citizens is a critical unresolved legal issue, and is fraught with important privacy, equity, and access concerns.

## Achieving Universal Access

While achieving universal access has proved to be challenging, recent technological advances, along with years of lessons learned, have the world poised to eliminate energy poverty related to electricity access within our lifetime, and provide everyone with enough electricity to extinguish the open flames of fuel-based lighting. The decentralized power network is rapidly forming with support from underlying energy technology, enterprises and institutions, ICTs, and other complementary systems. It enables the off-grid poor to redirect their current spending on inefficient sources of energy to modern electric power systems that meet their basic needs and more with lower barriers related to isolation and a significantly reduced environmental impact than was possible a generation ago [25].

In the IEA's "new policies" scenario, 1.8 billion people will be newly connected to centralized electricity by 2030, an impressive pace but one that is still projected to leave nearly 1 billion without a centralized connection [2]. Supporting adoption of decentralized power can bridge the gap, and in some cases replace the need for grid expansions that may take another generation or more to be completed. A number of agencies and organizations have calculated the potential costs of such an effort, with estimates ranging from 15-45 billion USD per year [2]. The investment would be less than 0.5% of the current annual GDP of the United States, or 0.1% of the global annual GDP [112] and is on par with current spending on fuel-based lighting and ad-hoc electricity use by people without access.

Such an effort will require more than just targeted aid funding and appropriate technology. Institutional frameworks will have to be developed at local, national, and regional levels to support energy access growth. National level policy measures like feed-in-tariffs, net metering, subsidies, and rural electrification funds will have to be coupled with international trade agreements, collaborations with mobile telecommunications companies around mobile banking infrastructure, and other public private partnerships. Governments will need to look towards novel sources of data to better inform evidence-based policy, especially with the advent of Big Data analytics. Donor countries will need to support large-scale private sector participation in emerging markets through political risk insurance, conditional grants, debt financing, and other financial mechanisms.

Support for private sector approaches to energy access off-grid today is in line with the trajectory that lead to rapid expansion of grid-based power networks in the past: a beginning with dispersed private approaches until a critical mass is reached and it becomes the task of the public sector to regulate and maintain the system. What is needed next is an expansion of the types of off-grid and mini-grid service providers, and a coordinated effort to gather real-time data from these new and often experimental efforts to build a practical, likely for-profit, network of energy service companies.

There are a range of key 'next step' research and field data-collection questions that this framework and emerging theory highlight. Each is an area where an expanded set of theoretical models would help greatly, and where practical, field-driven, data on both how energy service providers and consumers interact is vital, but largely absent today.

These include efforts to understand how: 1) technology development can be shaped and directed to further ease mobile payment, remote monitoring and maintenance, theft-protection, integration into grid systems, dynamic micro-grids that can expand and grow with user demand growth; 2) what micro-grid technologies would best facilitate user interaction, real-time data collection, improved energy efficiency, and remote management and system operation; 3) new approaches to studies can be built to assess how new electricity users move between tiers of service consumption and how their socioeconomic conditions change as a result of electrification, an area likely to fill squarely into the realm of 'big-data' analytics. Finally, there is an over-arching need for research into the financing of energy access, including the information gaps that exist for private investors, the current preferences and behavior of actors that could potentially provide capital for customers who – at least initially – consume very small amounts of energy (first users), but over time could become one of the largest and most dynamic sectors of change in the global energy economy.

Taken together this paper and the new research areas outlined above moves *towards a theory of energy access* that can inform strategies to shape and catalyze the trend towards decentralized power as it evolves in the coming decades. As new networks for energy access form and evolve, an awareness of the critical role of nested network structure and institutional dynamics can inform better interventions to provide power to the global poor while slowing degradation and harm of the ecological networks that underpin a growing population in the Anthropocene.

## Acknowledgments

We thank the Karsten Family Foundation for their endowment support of the Renewable and Appropriate Energy Laboratory, and the Class of 1935 of the University of California, Berkeley; this work was also supported by NSF Award SMA-1338539 and a grant from Humanity United (all to D.M.K.). P.A. is supported by a US EPA STAR fellowship award.

P.A. is a consultant to the Lighting Global program (described in the article) and is a core member of the Lighting Global Quality Assurance team, but this work was not supported under that contract and was not subject to review by Lighting Global or its funding partners.

We thank Doug Arent, Dan Arvizu, Morgan Bazilian, Anand Gopal, and Arne Jacobson and Amol Phadke for fruitful discussions about the implications of superefficient appliances in an off-grid context. Thanks to the Energy and Resources Group Ph.D. seminar participants and to anonymous reviewers and the editorial staff at *Science* for helpful comments.

The original data will be made available at http://rael.berkeley.edu and the analysis methods with source descriptions for the data are included in the Supplementary Materials.

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