ernment 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

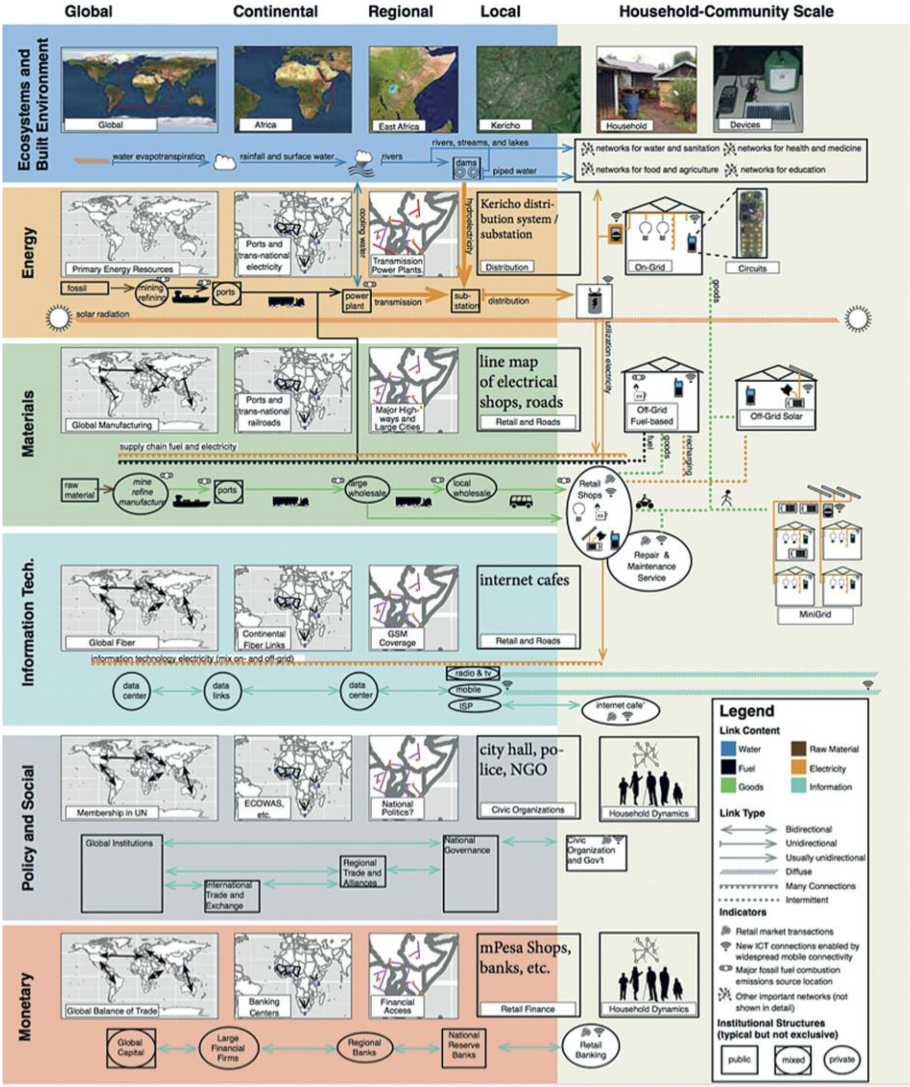

Figure 4. Multiscale, linked physical and information networks for energy access. This caricature zooms from global scale to a focus on households outside Kericho, Kenya but is meant to be representative of the dynamics for many other off-grid locations. [Note to editor: This is an evolving version of 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 $kT\ln 2$, 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 pico-power 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.

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