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Decentralized energy systems for clean electricity access

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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.

Two critically important and interlinked challenges face the global community in the twenty-first 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].

But 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—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 per cent 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. Unserved and underserved populations still primarily rely on low-efficiency open flames for lighting 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 recharging mobile phones[16,17], which are used by 72% of people in low-to-middle income countries, a 20-fold increase since 2000[18]. Mobile phones are a critical basic-needs technology, providing valuable services that link people with family, allow for participation in the market place through mobile banking and mobile money transfers, and permit 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 that 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 *et al.*[20], who demonstrated a clear correlation between human development and electricity consumption

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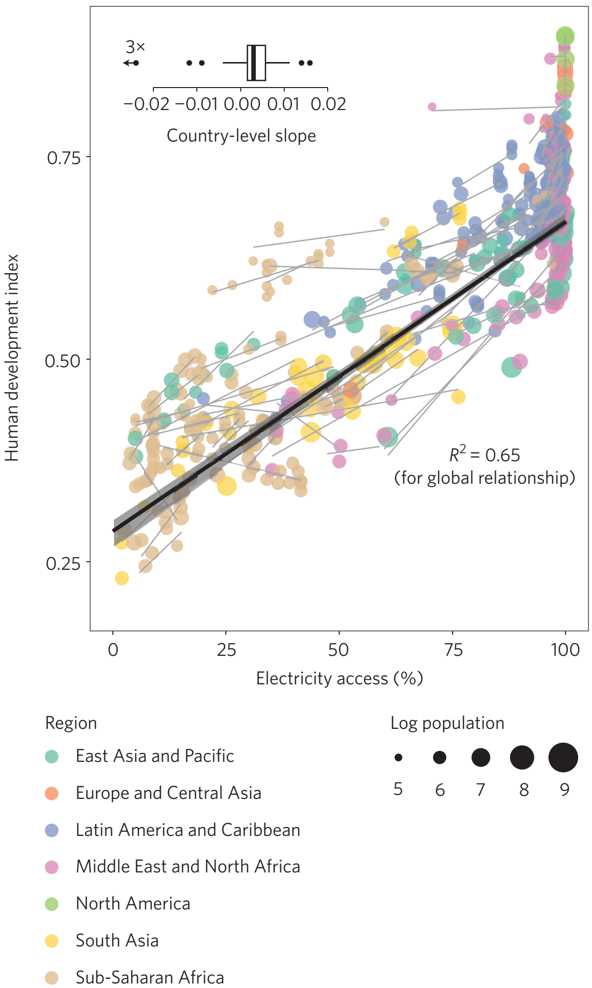

Figure 1 | The relationship between access to electricity and human development index (HDI) for 2000–2010. All the data points are on a country level for a particular time. The individual, country-level regression slopes over time are indicated on the figure, along with a full sample regression. The distribution in slope on a country level shown in the inset box plot indicates that 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 1.5 times the interquartile 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.

per capita (kWh per capita, which suggested a relationship with steep gains for the first 2,000–4,000 kWh per capita per year and greatly diminishing marginal returns to human development for consumption beyond that basic-needs level)[21]. The kWh per 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, Figs 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 a first-order linear predictor of human development index (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 people's lives, followed by less valuable applications.

Although 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, such as hospitals, schools and agricultural processing mills, 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/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 services contributing to quality of life[2].

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*[30]). 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 were developed in the late 1800s and early 1900s), and catalysed 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[31].

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 such as the United States Government Tennessee Valley Authority of the 1930s continue to be echoed today by work throughout the developing world, where the issue of access remains. Our analysis of the archival record in Fig. 3 shows that since the initiation of centralized electricity in the late 1800s, there have consistently been between 1 and 2 billion people without access (that is, 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 were completely off-grid[2], and many ostensibly connected people in the developing world experience significant outages accumulating to tens to hundreds of days per year[32].

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 International Energy Agency (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]. Sustainable Energy for All (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 solar home systems (SHS) and intra-household or 'pico-solar' products)[2]. The Global Energy Assessment by the International Institute for Applied Systems Analysis (IIASA) projects a slightly higher number of people unserved, with over a billion people lacking access in rural areas in 2030, and nearly 200 million in urban zones[33]. The scenario that we present in Fig. 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[34], 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 many rural areas of poor nations because of high marginal cost of connection compared with expected usage[35]. 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[36]. In fact, many households and businesses in 'electrified' areas lack access, even directly beneath power lines[37]. 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[35,38]. People and communities without property rights may lack the stability to justify investments in fixed infrastructure, or permission from central authority to do so.

The electricity 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 on a large scale, but these are connected to end-users by dynamic global supply chains and knowledge networks instead of fixed physical infrastructure.

Although dynamo generators and arc lighting, which perform best at large scale, catalysed the market for electric utilities, it is a range of semiconductors (stemming from the discovery of the transistor noted in Fig. 3) that has 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[39] (for example, see Fig. 3), d.c. televisions[40], refrigeration[41],

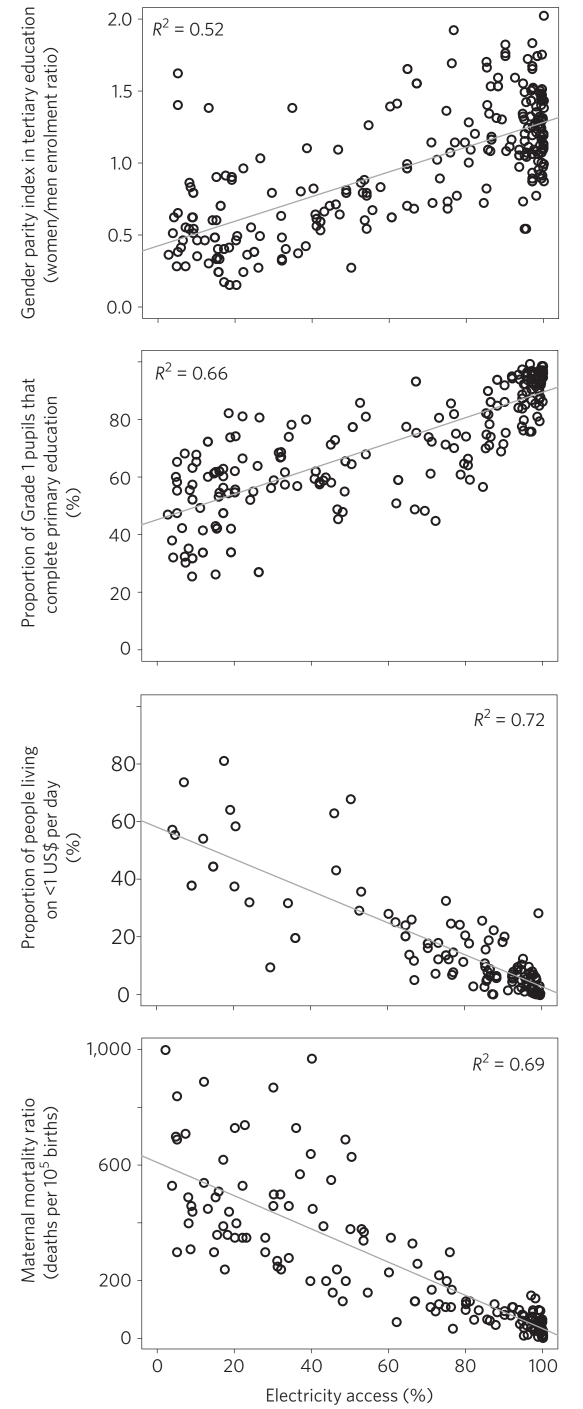

Figure 2 | The relationship between access to electricity and selected Millennium Development indices for 2000–2010. **a**, The ratio of women to men in tertiary (post-secondary) education. **b**, The percentage of students in Grade 1 who complete secondary education. **c**, Extreme poverty measured by the proportion of people living on less than US$1 per day. **d**, Death of mother per 10,000 births. All of the data points are on a country level for a particular time. The coefficients of determination (R^2) values for the full-sample linear regression are displayed on the figure panels. Additional development indices are found in Supplementary Fig. S1.

fans[42] and ICT[43] (a 'super-efficiency trend') enable decentralized power and appliance systems to compete with legacy equipment, on a basis of cost for energy service, for basic household needs. These

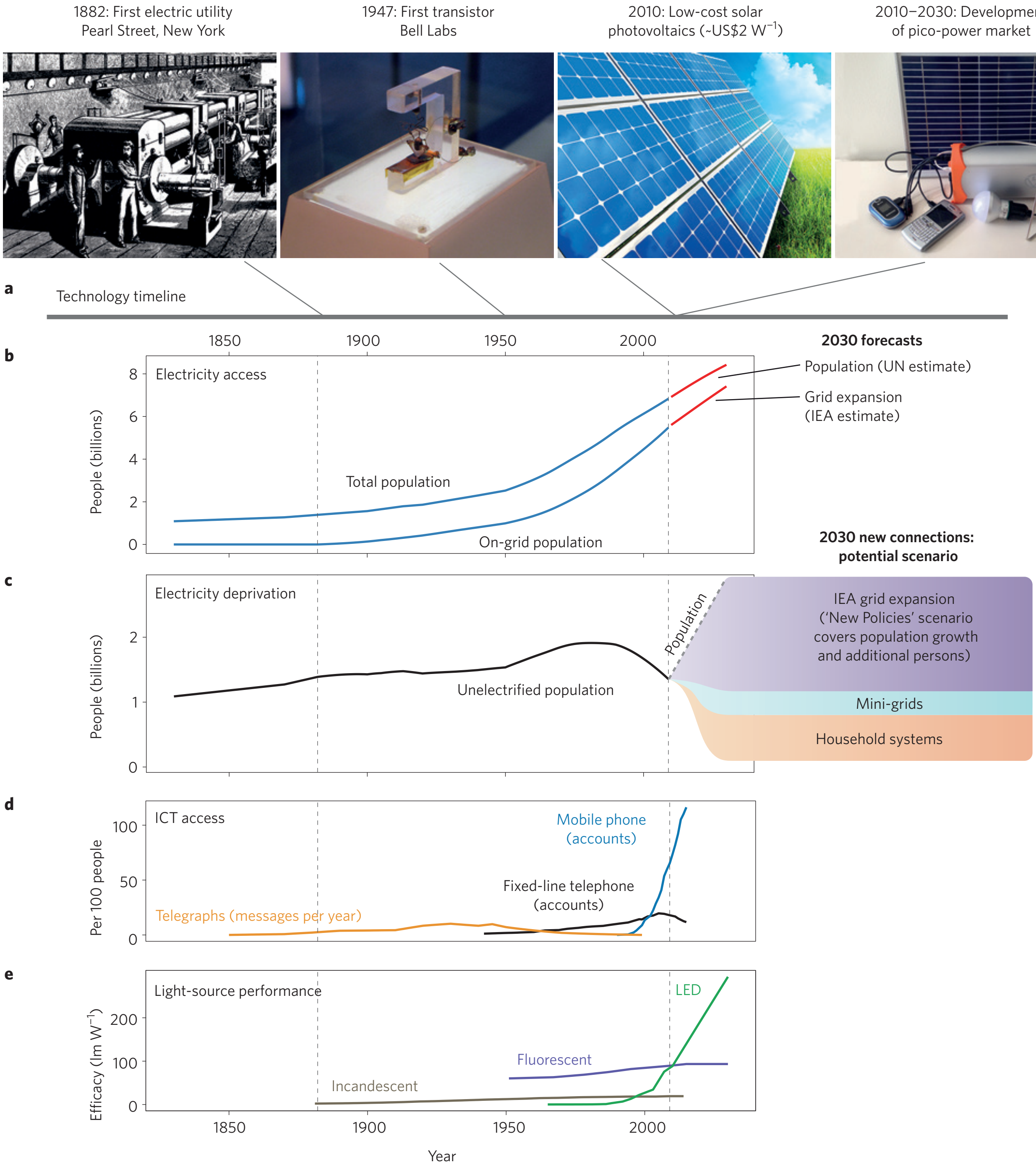

Figure 3 | Two centuries of historical trends and a potential future scenario from 1830 to 2030 for electricity access in the context of technology and supporting network events and trends. a, Technology timeline showing watershed moments of innovation and market paradigm shifts. **b**,**c**, The population with access to electricity over the time period, with **c** reflecting a potential future scenario for decentralized electricity development. **d**, A range of market penetration for ICT, going as far back as telegraphs (a primary enabling technology in the spread of electric grids). Mobile phones, also shown, are the contemporary alternative to centralized systems. **e**, 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. Images in **a** from left to right © bilwissedition Ltd. & Co. KG / Alamy; Windell H. Oskay; GettyImages/iStockphoto/Thinkstock Images; Peter Alstone.

rapid advancements in basic technology supporting clean energy both on- and off-grid are predicted to continue[39,44,45].

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 systems (PLS)[11], SHS, and community-scale micro- and mini-grids[2,3]. Although 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 with the status quo. Table 1 is a synthesis of how the continuum of technology is often divided for analysis, and how each

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.

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 Geographic: Low barrier. Requires distribution to remote areas through normal supply chains with some markup Political: Low barrier. Government 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 US$10–100 Geographic: Low barrier. Requires distribution to remote areas Political: Low barrier. Government 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 US$75–1,000 Geographic: Low barrier. Requires distribution to remote areas Political: Low barrier. Government 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: for example water pumping or grain milling	Economic: Medium to high barrier. Requires financing or investment aggregation for large capital outlay but offers relatively low marginal cost electricity to users Geographic: Medium barrier. Requires critical density of population 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 can add significantly to the connection cost in sparsely populated areas Geographic: High barrier. Requires nearby transmission and distribution infrastructure Political: High barrier. Depends on ministerial and departmental decisions about extension

The descriptions are a synthesis from the authors' experience and research.

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.

Meeting people's basic lighting and communication needs is an important first step on the 'modern electricity service ladder'. Eliminating kerosene (paraffin) 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 less costly than fee-based recharging, by at least a factor of 10, on a dollar per kWh basis for electricity (US$100 per kWh for fees at a shop compared with ~US$10 or less for the levelized cost of electricity as shown in Fig. 4b). This frees income and also tends to lead to higher rates of use for highly valued mobile phones and other small devices[46]. Overall, the first few watts of power mediated through efficient end-uses lead to high marginal benefits in household health, education and poverty reduction[16,47]. Beyond basic needs, there can be a wide range of important and highly-valued services provided by decentralized power (for example television, refrigeration, fans; heating, ventilating and air conditioning (HVAC); and 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 per day for mobile phone charging or the first 100 lmh of light—as indicated by the regimes of incumbent technology consumption versus cost noted in Fig. 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)[48].

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 is likely to change as well, with a reduced slope as the cost for small-scale power decreases.

The critical role of super-efficient lighting for amplifying the service capabilities of power systems is highlighted in Fig. 4c and is indicative of similar trends across other appliance types. It shows how a hypothetical person who consistently invests US$100 per year for lighting shifts from an energy 'investment' of over 2,000 Wh per day (as liquid kerosene fuel) for 100 lmh of lighting service to 20,000 lmh with a grid connection and incandescent bulb or 100,000 lmh with high-efficacy LED lighting. LED lighting functionally enables off-grid pico-power systems to offer the rural

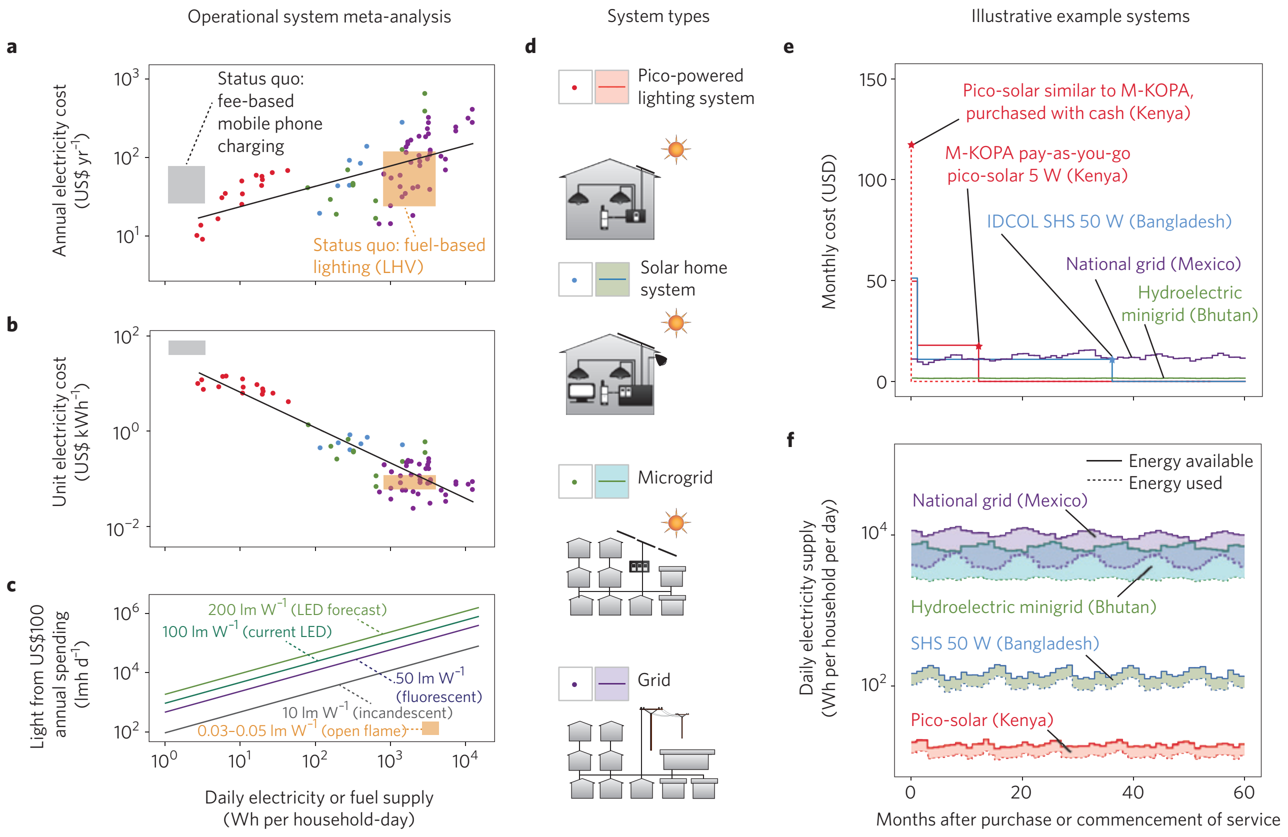

Figure 4 | Five views on the continuum of electricity access based on real-world system operations. a,**b**, The annual (**a**) and unit (**b**) costs of electricity. The incumbent options (fuel-based lighting and fee-based charging) are included for reference, with fuel-based lighting in terms of lower heating value for typical fuel consumption ranges[12] and fuel prices[67] with ±50% bounds to account for variation. **c**, The implications of super-efficient 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^{-1}). **d**, System pictograms of grid types. **e**,**f**, The cost structure (**e**) and electricity provided (**f**) for illustrative examples: 5 watt solar pico-power system in Kenya (with and without PAYG financing), 50 watt SHS 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 the Supplementary Material.

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[49]. Historically (and currently, in many cases), the non-technical barriers to adoption have been as great, or greater, 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[49–51]. Furthermore, complex and often perverse policy environments impair entry for clean technologies and entrench incumbent systems (for example subsidies for liquid lighting fuels that reduce the incentive to adopt electric lighting[52]). Finally, the prevalence of imperfect or inaccurate information about quality can lead to market spoiling[53] 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 Fig. 5, where we demonstrate the growth trajectory of commercial sales supported by three particular approaches from 2004 to 2014. These include: country-targeted support such as the IDCOL programme (SHS financing and subsidy programme in Bangladesh), global market transformation such as Lighting Africa, and next-generation pay-as-you-go solar businesses such as M-KOPA that use mobile money and new delivery models for end-user asset financing. With tens 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 (for example mobile phones) and supports the potential future scenario shown in aggregate in Fig. 3c, with rapid expansion in household and community-scale decentralized power.

In Fig. 4e and f we show the payment and service dynamics for the off-grid systems highlighted in Fig. 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[54]. 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).

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 are 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 remotely activated cut-off switch in the system hardware that prevents use when fees or loan payments have not been completed[57] (for example the M-KOPA system highlighted in Fig. 4e). This reduces the transaction costs for providing and enforcing small loans, and essentially passes retail working capital finance on to the consumer. The payment stream for PAYG off-grid power is 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 people's ability and willingness to pay in the context of uncertainty and careful budgeting of scarce cash[59]. Some systems include remote monitoring features, enabling better knowledge about user behaviour 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 are enabled through integration of on-board sensing and communication technology. These platforms can enable predictive and responsive maintenance, addressing a common barrier to durable energy access for 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 platforms for reporting issues, 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-grid will also require new ICT tools. An early example of off-the-grid responsive demand is the GridShare pilot project in Bhutan

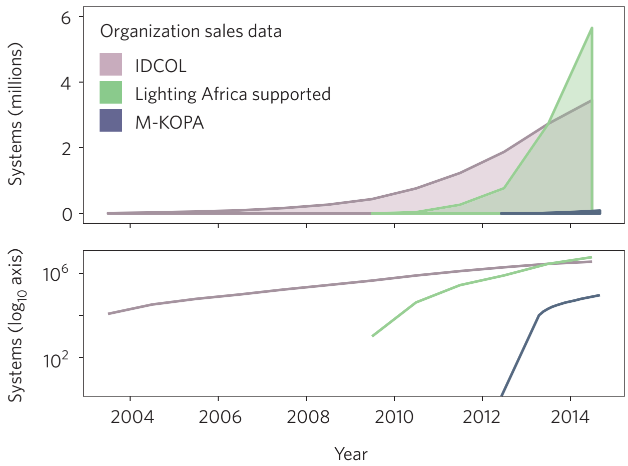

Figure 5 | Sales of household off-grid systems as reported by organizations active in market-based distribution. The log axis shows similarities in early growth rates between IDCOL (a SHS financing programme in Bangladesh), the Lighting Africa programme (a World Bank Group market transformation effort) and M-KOPA (a PAYG solar business in Kenya).

(shown as an example in Fig. 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 micro-hydro generator during cooking times with electric rice cookers[54]. 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 aid in 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 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. Although 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 to 2006 (Kenya Integrated Household Budget Survey, 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[48]), 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 example as an extreme case to simulate a full rebound in spending on lighting, whereas in reality we expect that in response to vastly improved efficiency, individuals would reallocate savings to much broader categories of

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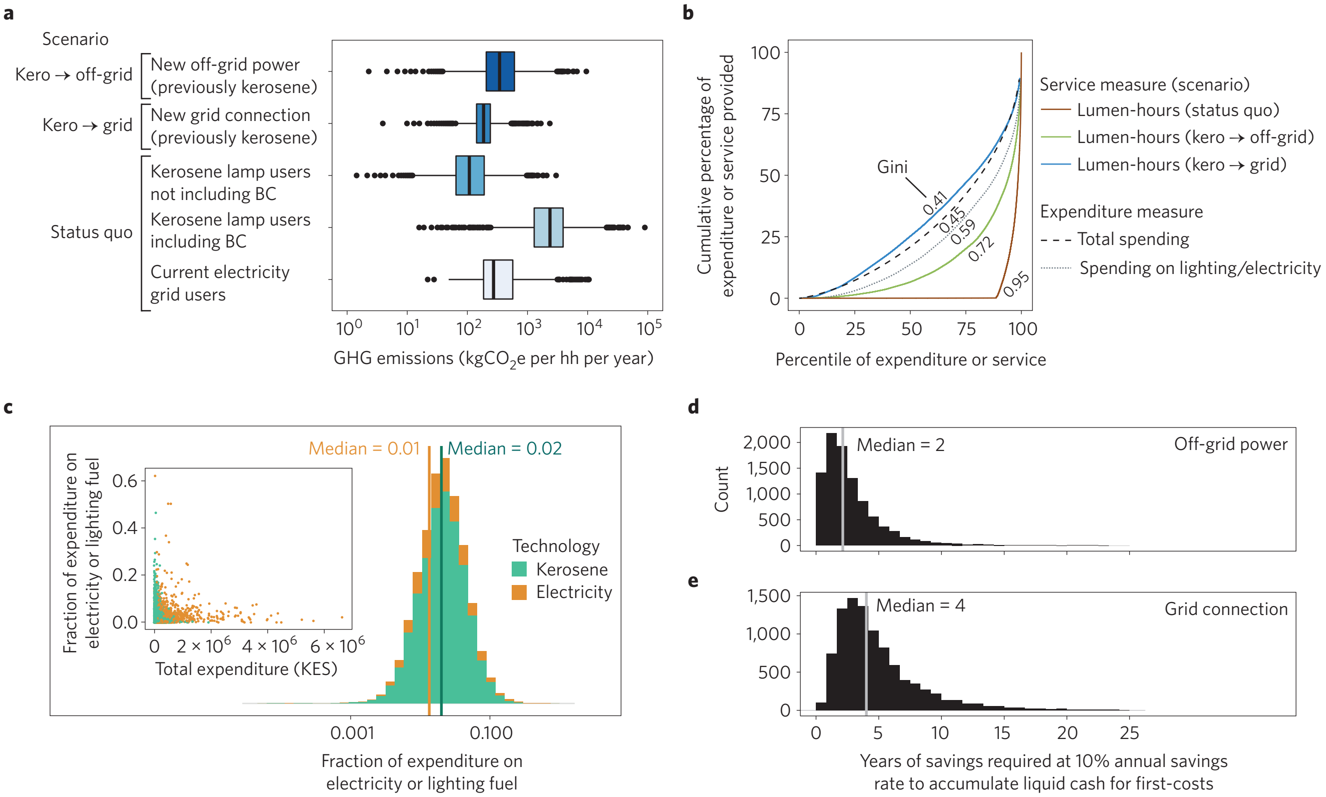

Figure 6 | Results from a simple model of climate impacts and adoption dynamics for electricity and lighting technology in Kenya. The base data are from the Kenya National Bureau of Statistics (KIHBS 2005/06, $n = 13{,}430$). **a**, Expected range in GHG emissions induced by household (hh) electricity or lighting use, with box plots demarcated at the 25th, 50th and 75th percentiles and whiskers to 1.5 times the interquartile range with outlier points. The status quo scenario shows emissions with and without accounting for black carbon (BC) emissions from open-wick lamps that comprise 55% of the lamps in use. **b**, 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 *et al.*[66]. **c**, Fraction of expenditure devoted to kerosene and electricity in the status quo scenario for primary users of both. The inset scatterplot shows that the poor tend to spend a higher fraction of income on energy. **d**,**e**, Implied number of years of household savings at a rate equal to 10% of expenditure to accumulate cash for upfront payments for (**d**) off-grid and (**e**) grid power. In **d**, we assume cash sale of system with levelized cost equal to ongoing kerosene expenses. In **e**, we assume a fee of 35,000 KES (minimum fee without need for additional poles and other equipment).

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. Figure 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, it appears that kerosene users induce substantially lower emissions than those connected to the grid. However, when the effects of black carbon are accounted for (using 100-year global warming potentials), climate forcing from households using kerosene lighting appears nearly 10 times as high as that of 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 great improvements in equality of access to service, as shown in Fig.6b, which shows variations in access in terms of Lorenz curves and Gini (income inequality) 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 Fig. 6c, which indicates that 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 because of 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 super-efficient 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 meets or exceeds their expectations and builds 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 6d shows the high hurdle of up-front costs of systems for which the poor have demonstrated an ability to pay, based on the kerosene expenditures reported in the survey. The reality that we observe in the field is that many people choose to invest in systems that offer lower service levels than 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 with 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 Fig. 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 from the incumbent system, challenging the conventional knowledge held by some that one must choose between progress on energy access or climate.

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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.

Additional information
Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence should be addressed to D.M.K.

Competing financial interests
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