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The costs and benefits of lighting and electricity services for off-grid populations in sub-Sahara Africa

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Question

What are the relative costs and benefits of delivering different types of lighting and electricity services to off-grid populations (comparison by source – i.e. renewables, diesel – and by scale – i.e. mini-grid vs solar home systems vs smaller scale options) and how are these expected to evolve over time?

Contents

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1. Overview

The current scale of investment of US$15–19 billion per year will still leave 350–600 million people without access to electricity by 2030, who live mainly in rural sub-Sahara Africa. The attention of efforts to achieve the universal access to energy target, therefore, focus on technologies that go beyond the centralised system approach. Evidence from literature shows that grid-based electrification is only an attractive option in densely populated areas, with an expected high demand for electricity, and/or within reasonable distance of existing high voltage power lines. Large parts of sub-Sahara Africa do not satisfy these criteria, with large, sparsely populated rural areas in which many households have a very low income. Thus, the literature shows that population density and electricity demand are important factors for decision-making on the cost-efficiency of off-grid technologies.

- Stand-alone pico-solar lights put off-grid populations on the first step of the energy ladder, while making significant savings on kerosene, dry-cell batteries and candle costs and improving lumen/hour light quality.
- Solar Home Systems (SHS) are more expensive, but with pay-as-you-go models for the poorest households the technology is affordable up to around US$150 for a three years pay period. The households benefit in that they will own the system and appliances after the pay period without making further payments.
- Some other benefits that the literature mentions regarding the shift to stand-alone solar PV solutions: better health, more hours of light used for education and productive work, opportunities for women mainly through an increase in mobile phone usage.
- Investments into mini-grid systems for poor populations that live remotely in sub-Sahara Africa are currently not cost-efficient (although with lower kWh/year). Expensive higher voltages connections do not fit the current demand of these populations, which does not justify the high initial investments needed for mini-grid technologies.
- The literature shows that increasing population density and demand could make mini-grid solutions competitive with the larger solar home systems - especially if rural mini-grid electrification programmes can be designed and implemented and operated effectively.
- A number of substantial barriers to up scaling have been identified in the literature. Diesel prices are volatile and trending up and the associated transportation logistics which substantially increase its cost in remote locations are a substantial burden for utilities and consumers. Cost reduction for renewables over the last years, make them the most competitive solution to generate mini-grids in regions with high diesel prices; with biomass/gas and mini-hydro technologies accounting for the lowest unit cost.
- The literature shows further that mini-grids powered by renewables (also in hybrid systems combined with diesel) pollute less, are more reliable and therefore increase willingness to pay for customers.
- Current trends of falling prices for renewable solutions, combined with better quality and higher diesel and kerosene prices is likely to continue and could spur electrification in off-grid regions as in particular solar PV systems are highly price elastic.
- Furthermore, new technologies will be introduced in the next years, varying from swarm electrification, smart solutions with the use of real-time data collection, creating opportunities for innovative business models.

The literature (academic and grey) does not aggregate data on gender, although some studies found evidence on impact of better quality lighting and access to electricity for women. This report has a special focus on sub-Sahara Africa. Extensive literature can be found with evidence from off-grid electrification programmes in Asia, in particular in India, Sri Lanka, Bangladesh and China. Such literature has only in a few occasions been included in this report, because of the geographical and social-political differences between the regions.

2. Context and types of off-grid electricity and lighting systems

Gaining access to electricity and lighting

The International Energy Agency (IEA) found that over 100 million people worldwide per year have gained access to electricity since 2012 compared with around 60 million per year from 2000 to 2012. However, 1.1 billion people worldwide remain without access to electricity; a number that is expected to go down to around 675 million people in 2030 – 90% of them in sub-Saharan Africa (IEA, 2017, p.6). That means that two in every three people in sub-Saharan Africa do not have access to electricity (Lucas et al, 2017, p.6). 85% of the unserved population lives far away from the power grid in rural areas (IEA, 2010, p.237), because of the high costs for grid extension, which is not balanced by a local market. The remaining 15% lives closer to the grid, but cannot afford the high connection fees (sub-Saharan Africa costs are around US$400 – IRENA, 2016, p.53) or metering and wiring costs (US$100, Lucas et al, 2017, p.34).

To achieve universal access to energy by 2030, the World Bank estimates that the pace of connections in low-access countries (mostly in sub-Saharan Africa) needs to rise from the present average of 2 million per year to about 15 million per year for the next 15 years. This translates to an increase of investments from US$3.6 billion per year to about US$37 billion per year (World Bank, 2015, p.2), depending largely on the assumed level of electricity consumption by the additionally connected households. Other literature confirms the scale of investment (Lucas et al; US$9-33 billion per year; 2017, p.42) as the current US$15–19 billion per year of investments will leave 350–600 million people without access to electricity by 2030. The World Bank concludes: “This huge increase in connections is unlikely to result solely or predominantly from grid expansion alone in the time frame set by global access goals” (World Bank, 2015, p.2).

The attention of efforts to achieve the universal access to energy target, therefore, focus on technologies that go beyond the centralised system approach. The IEA highlights that 315 million people in rural areas are expected to gain access to electricity, around 80 million (25%) through stand-alone off-grid systems, and around 140 million (44%) through mini-grids – an extra 100,000 to 200,000 mini-grids - providing the first step in the electrification process and a building-block for future grid development (IEA, 2014, p.496).

Types of off-grid electricity and lighting systems

A multitier framework for defining and measuring the level of access to electricity was introduced through the Sustainable Energy for All initiative. It distinguishes five levels of access from tier 1 to tier 5. Each tier is differentiated by the typical electricity end uses that can be powered and the associated number of hours per day for which that access should be available (World Bank, 2015, p.5). Tier 0 refers to a household without access to electricity that relies on the purchase of kerosene, candles and dry cell batteries for lighting. A household in tier 1 has access to an energy source to light a small lamp, charge a phone and listen to a radio. Tier 2 adds the use of general lighting, a television and fan. At the end (tier 5) the use of the full range of modern appliances such as air conditioners and large refrigerators is possible. The quality of services also improves along the scale, with tier 1 and 2 services available for at least four hours a day, and tier 5 services for 23 hours a day.

Moving from tier 0 up-wards is in the literature referred to as moving up the energy ladder (e.g. Harrison, 2016, p.7; World Bank, 2015, p.5; Grimm et al, 2016, p.1). The literature distinguishes three types of off-grid electricity and lighting systems that support people to set the first steps on the energy ladder:

- Pico-solar systems (Tier 1: 1-10 Watts)
- Solar Home System (Tier 2-3: 10-100 Watts)
- Isolated micro- or mini-grid systems (Tier 3-5: 100-1000 Watts).

Mini-grid systems can be solar, hydro, wind, biomass or diesel generated or based on a hybrid system. Such systems should be combined with a battery storage and supply multiple households with Direct Current (DC). The pico-solar and Solar Home Systems (SHS) supply a single household as the system is installed on the premise. Pico-solar systems use Alternating Current (AC), while SHS can be DC and AC.

The literature questions the “grid versus off-grid” trade-off. Grid and off-grid technologies and access service delivery are not necessarily either-or options to be determined simply based on a narrow least-cost calculus (e.g. World Bank, 2015, p.34; Leo et al, 2018, p.16; Chattopadhyay et al, 2015, p.44). Off-grid electrification can play a significant role in most low-access countries and the customers may appreciate the lights and basic appliances that off-grid systems can power, but they want to move up the energy ladder toward higher power appliances enabled by a grid connection. At the same time, on-grid customers face a host of reliability issues and thus see off-grid options as an important backup (Leo et al, 2018, p.10).

Market trends

Current off-grid electricity and lighting systems have a 90% reliance on renewable-based home systems and mini-grids. In 2016, growth in solar photovoltaics (PV) capacity was larger than for any other form of generation (IEA, 2017, p.1). The main reason is that the economic case for all forms of solar electricity has vastly improved, with solar panel costs falling over 50% in real terms over the last 5 years. The rapid deployment of solar PV is anticipated to help solar become the largest source of low-carbon capacity by 2040, by which time the share of all renewables in total power generation is expected to reach 40% (IEA, 2017, p. 2). Since 2012 there was also a significant cost reduction for wind energy by 25% and battery costs by 40% (IEA, 2017, p.1).

The World Bank (2015, p.7) signals the “coming of age” of off-grid stand-alone electricity and lighting systems with options that are market-proven for effectively achieving tier 1 and tier 2 market access. From a near-standing start less than 10 years ago, more than 100 companies are now actively focusing on stand-alone solar lanterns and SHS kits targeted at those without modern energy access. They have sold over 14 million quality-certified pico-solar products (with a PV panel smaller than 10 Watts), mainly portable lights (World Bank, 2015, p.11).

For sub-Sahara Africa, the industry for pico-solar lights and SHS barely existed a few years ago, but SHS were sold to around 600,000 households in Africa (The Economist, 2015). In terms of total sales the market has been led by pico-solar lights, but business model innovations such as pay-as-you-go (PAYG) financing are increasing the sales of the SHS also in Africa. Globally, reported unit sales of 3-10 Watt multi-light solar systems have increased 5-fold in 2016, while conversely, there has been a decrease in sales of 0-3 Watt single light products (Harrison et al, 2017, p.13).

Focussing on the African pico-solar and small SHS markets, the literature mentions the following considerations:

- The market of stand-alone off-grid electricity and lighting systems is not only for off-grid populations. One study found that 15% of the customer base of a company that sells SHS in East Africa was already connected to the grid (based on Acumen Lean Data; Harrison et al, 2017, p.12).
- East Africa represents about 70% of total sales volume in sub-Sahara Africa and 77% of revenues (GOGLA, 2016). PAYG SHS companies are most prevalent in Kenya, Tanzania, Rwanda and Uganda (Harrison, 2017, p.13).
- Consumers of stand-alone systems are confronted with limited choices. Choice options tend to dwindle the further consumers are from urban areas (Harrison, 2017, p.13).

3. Consumption and expenditures

Traditional energy sources for off-grid households

The research on rural household energy consumption in the millennium villages in sub-Saharan Africa indicates that on average households spent more on lighting and electricity (US$48) than on cooking (US$21) per year (Adkins et al, 2012, p. 253). Kerosene is the main fuel for lighting purposes, on average lighting the household for 27 hours a week - with East Africa above average and West Africa below average (where households make often use of torches and candles). Dry cell batteries are being used for 10 hours of light a week, while candles just count for 2 hours and rechargeable batteries were not used for lighting, purely for mobile phones.

Adkins et al found that on average households' expenditure on kerosene is US$27 a year, on batteries US$19 and on candles US$4. However, kerosene prices vary between countries (due to subsidies or import taxation) and notably between regions. Kerosene prices are an estimated 46% higher in rural areas of Africa compared to urban areas (Harrison, 2017, p.19). UNEP's (2013) off-grid lighting country assessments estimate an average of US$71 a year spent per household on kerosene. A kerosene lamp with glass cover consumes 0.030 litre/hour and a simple wick lamp 0.025 litre/hour (UNEP, 2013, p.6).

Other studies show that rural households in sub-Sahara Africa on average spend US$6-9 a month on total energy of which US$4-5 for lighting of which 90-95% for kerosene, candles (US$0.10 per unit) and batteries (US$0.50 per unit (UNEP, 2013, p.6; Harrison et al, 2017, p. 19). For this expenditure they get in turn brightness 20 lumens for a standard kerosene lamp, a single-wick lamp 10 lumens, candle 10 lumens.

Pico-solar lanterns and pico-solar home systems

A Pico-solar lantern/light is a standalone light product. Pico-solar light providing 20 to 100 lumens, depending on the product and setting used. A Pico-solar home system includes an easy to install small solar panel, battery and charger for a mobile phone, light or radio. There are several companies that sell these products to rural populations in Africa. The price depends on the capability of the product and the extra services the company offers, like micro-credits, purchase of a radio and lights, guarantees and delivery.

Most of the solar lanterns now are equipped with LED lights and are sold between US$5-20. They should work for over 5 years. For example, GreenLight Planet is a global business that designs and manufactures its own pico-solar lights and sells them from US$8. SunnyMoney, the social enterprise of SolarAid, sells pico-solar lights from US$5-35. They distribute manufacturer products including d.Light and Greenlight Planet, but have also produced their own solar light, the SM100, funded by Yingli, which they sell for US$14. d.Light offers its newest pico-solar light, the A1 for US$7.

Pico-solar home systems sell in the market around US$50 for systems with a capacity of 1-2 Watt and around US$100 for systems with a capacity of 4 Watt, and just under US$200 for systems with a capacity of 10 Watt (IEA, 2013, p. 21). The panels should last for 25 years running above 80% of their capacity. For example, GreenLight Planet has a pico-solar system on the market for US$109. M-Kopa's system is US$199.25 and integrates a PAYG model with M-Pesa mobile money platform. Customers pay an initial US$35 deposit, followed by 365 daily payments of US$0.45. In return, they receive a solar home system that includes multiple lights, a phone charger and a radio. The client owns all the product. Mobisol, Azuri and d.Light work in more or less a similar way.

Off-grid Electric which operates in Rwanda and Tanzania works in a different way. Clients pay US$6-9 installation fee, followed with a daily fee between US$0.18-0.63. Off-Grid Electric guarantees service for the lifetime of the product and operates a 24/7 call centre to respond to customer needs. The package also includes a meter to keep track of energy usage, LED lights, a radio and a phone charger. This solar-as-a-service model means customers do not own the system.

Solar Home Systems (SHS)

The majority of the SHS sold in Africa today are believed to be in the 20 Watt to 100 Watt range. The cheapest 20 Watt system costs around US$225, while for a 100 Watt system the total cost ranged from US$725 to US$1,270 (IRENA, 2016, p. 41). The system specifications of individual SHS can vary widely, with inexpensive entry-level systems offering smaller battery storage capacity to reduce costs and increase affordability.

The IRENA report also mentions that below 100 Watt the systems are relatively homogeneous, focusing on low upfront costs. At around 100 Watt or greater product differentiation begins, with a range of systems with greater or lesser capability based on battery size and service provided (IRENA, 2016, p.41). However, for rural off-grid sub-Sahara African households these systems are out of reach.

Battery costs account for the largest single share of these SHS, with a simple average of 29% of the total costs (US$2.7/W). The PV modules themselves, as well as the lighting fixtures and wiring, are on average around 20% (US$2.2/W) of the total installed costs, soft costs account for 22% (US$2/W), other hardware for 21% (US$2/W) and the charge controller for 7% (US$0.7/W) (IRENA, 2016, p.44). This means that a battery failure, which is one of the most common defects that occur with SHS, can have a significant replacement cost for households.

Distributors, sellers and retailers of SHS in sub-Sahara Africa mostly work with a PAYG model with a small deposit to be paid upfront. A smaller group of providers (Solar Kiosk; Off-Grid Electric) work according to a solar-for-service model in which the clients do not own the system, which spares them from any reparation or renewal costs. Comparisons on the international level are difficult since there appears to be significant variations in cost of SHS across different programmes and different regions and countries. But the literature shows that SHS costs seem to have generally been lower in Asia than in Africa. The cost estimates suggest a range somewhere between US$350 and US$400 for a 50 Watt system with a three- to five-year guarantee on battery life and maintenance support in Bangladesh and India. Costs in for example Uganda and Senegal have been reported to be in the range of US$500–600 for a 50 Watt system (Chattopadhyay, 2015, p.43).

Mini-grid systems

Mini-grids have a longer history than SHS as a solution for electrifying rural or remote island communities out of reach of the main grid. The literature signals that a cost analysis for mini-grid systems is more complicated. In contrast to the entrepreneurial impetus that is driving the growth of stand-alone home energy systems, cost calculations of mini-grids depend on technology and geographical location and require more planning and institutional context - a framework to ensure agreement on planning, operating, pricing and maintenance - as they serve a community of users (PwC, 2016, p.13).

With the exception of those located next to local sources of hydropower, such as in Nepal and Sri Lanka, they have typically been powered by diesel generators. In Africa in particular, mini-grids rely on diesel (e.g. Mali is an example often used in literature with 200 diesel generated mini-grids). The exact costs vary for different geographical locations, because diesel relies on fuel transport for operation. Different schemes on diesel subsidies and taxation also result in countries having very different diesel cost prices. For instance, diesel pump price variability across Africa includes lows of 0.1 US$/litre (Libya, subsidised cost) and highs of almost 2 US$/litre (Malawi and South Sudan) with a continental average of 1.18 US$/litre (Nerini et al, 2016, p.258).

Without subsidy policies, the literature shows that the lower running costs of renewable systems could give them an advantage over diesel (Cader et al, 2016, p.19). To compare the costs of different technologies the *levelised cost of electricity (LCOE)* is used, which allows project developers to compare the cost of electricity produced by different generation technologies with varied capital costs, fuel costs and lifetimes. Table 1 shows the ranges of LCOEs for village mini-grid technologies.

The advent of cheaper renewable power technology has seen the emergence of hybrid mini-grids (combining diesel and renewable generation) and renewables-only mini-grids. The literature concludes that hybridisation with renewables has positive impacts in reducing generation costs (it reduces wear and tear on the diesel generators, reducing maintenance costs and extending their operational lifetimes) and falling technology prices will further ease cost issues. One study found that LCOEs are reduced by a global average of EUR 0.14/kWh, with countries such as Chad, Mali, Central African Republic, Malawi and Niger that benefit the most of hybrid systems seeing a reduction of over EUR 0.40/kWh (Cader et al, 2016, p. 18).

Including a battery in solar PV-diesel hybrid systems is only economically feasible as the share rate of solar PV is above 45% (Cader et al, 2016, p.19). Maximisation of the diesel fuel savings of hybrid systems ensures that the diesel generators are operating only when they are needed and that they run at their most efficient level. This type of integration of solar PV-diesel hybrid systems with battery storage necessitates a more complex system design and operational strategy, but has been found to be more cost-effective (Hazelton et al, 2016, p.226).

Data from the first installed solar PV mini-grids in Africa show that off-grid systems under 124 kW have the largest cost variation, while the cost variance declines as system sizes increase (IRENA, 2017, p.57). Off-grid mini-grid projects without battery systems are often in place to maximise the solar PV fraction of demand in order to reduce diesel costs. The smaller-scale system has a high cost structure, but the larger installed systems have a competitive cost of US$1.4/Watt. The solar PV modules for these systems costed between US$0.7 and US$1.7/Watt and soft costs were low at between US$0.1 and US$0.4/Watt (IRENA, 2017, p.58). Including batteries shows a wide variation in total costs, particularly due to the variation in battery costs, module costs, and soft costs (IRENA, 2017, p.60).

Table 1: Relative cost of energy across mini-grid technologies

Resource	LCOE – low (US$/kWh)	LCOE – high (US$/kWh)
Wind	.043	.076
Hydropower	.057	.070
Biomass	.085	.125
Geothermal	.043	.053
PV	.058	.143
Solar thermal	.177	.373
Nuclear	.096	.104
Natural gas	.052	.148
Coal	.103	.196

Source: mentioned on the USAID website https://www.usaid.gov/energy/mini-grids/economics/levelized-cost (US Department of Energy (DOE) Energy Information Administration (EIA), 2017)

4. Cost comparison between technologies and scale

Cost comparison between technologies and scale is mostly done in literature in US$/Watt or US$/kWh. The literature that analysed the cost model of different technologies and scale show that population density is a key factor for the cost-competitiveness of solutions. For instance, an increase in population density from 100 to 500 households/km2 results in cost reductions 5% and 65% per household for mini-grid based solutions, depending on the technology (Nerini et al, 2016, p. 259). Nerini et al conclude that:

- Achieving the highest energy access targets (Tier 5) can be fifty to a hundred times more costly than achieving entry-levels of energy access (Tier 1) on a per connected household basis.
- Providing energy access using grid and mini-grid solutions for a Tier 1 situation can cost in excess of 10 US$/kWh. Solar PV and diesel stand-alone solutions have LCOEs ranging from 0.4 to 0.5 US$/kWh, making them far more economically feasible solutions in the attempt to access a Tier 1 situation.
- Access to Tier 2 situations it different; only in cases of low population density stand-alone solutions stay economically feasible. Solar PV (2250 kWh/m2/year) stand-alone systems are the best option in such situation. However, mini-grid-based systems become more competitive at higher population densities. Stand-alone solutions continue to lose in cost competitively across higher energy access targets, as most mini-grid and grid solutions already have LCOEs below 0.4 US$/kWh for Tier 4.
- Local grid characteristics, namely local grid electricity price and distance between the settlement and the grid connection point, will influence the competitiveness of grid connection for energy access.
- Hydro mini-grid solutions have the lowest LCOE in Tier 2-5 situations, being the most competitive technology (but only available at specific geographical locations) with the exception of a low population density area in a Tier 2 situation. Instead, biogas mini-grid installations have the lowest LCOE in low population density areas with a turning point at 400 households/km2 in a Tier 2 situation.
- Diesel mini-grid systems (at a low price tag of 0.5 US$/litre) are the second favourable solution in the lowest population density areas up to 100 households/km2, when wind generated mini-grids (cf=0.3) become more preferable in a Tier 2 situation. In this situation with a low diesel price, with growing population density, diesel has a slightly lower LCOE than solar PV (2250 kWh/m2/year) for a mini-grid in a Tier 2 situation.

See for figures and maps in the appendix.

5. Affordability and willingness to pay

Affordability

Poor households tend to spend a higher proportion of their income on energy, often for vastly inferior levels of energy services, like kerosene and candles (Alstone et al., 2015, p. 312). The poorest quintile of Kenyan consumers spent around 10% of their total expenditure in energy compared to the average across all households of around 5% (Harrison, 2017, p. 21). It also shows that price is the most important factor for households to decide not to purchase stand-alone solar PV electricity and lighting systems. The demand for solar lights is highly price elastic (Rom et al, 2017, p.2).

SolarAid's market research (2012-2015) with rural consumers across Kenya, Uganda, Tanzania, Malawi, Zambia, and Senegal shows that families spend an average of US$4 each month on lighting alone (Harrison et al, 2017, p.19). Similarly, Lighting Africa (2011) surveys conducted in Ethiopia, Kenya and Zambia found that a typical off-grid household spend on average US$4.75 monthly on lighting costs which increases to US$6.25 when mobile phone charging costs are included (Harrison et al, 2017, p19). In aggregate, the Overseas Development Institute (ODI) report estimates that African low-income households are spending around US$6.5 billion a year on inefficient lighting. This estimate is based on an average of US$50 a year per household and 130 million off-grid households (Harrison et al, 2016, p.8).

The Energy Sector Management Assistance Programme (ESMAP) 2015 report shows that electricity offers 10 times more affordable lighting than fuel-based lighting in terms of cost per lumen-hour (looking at cost, quality, and time). Replacing most of the traditional lighting costs (Tier 0) of around US$4 monthly with a pico-solar light (Tier 1) of around US$10 that works between 3-5 years and a SHS of around US$150 with PAYG service for three years is economical feasible and increasingly affordable for poor households.

Recent market studies show evidence that poor families indeed have entered significantly into the market. SolarAid's market research (2012-15) with pico-solar light customers suggests that an average family purchasing a basic pico-solar light has a monthly household income of around US$111, estimating that 77% of their customers live below the US$1.25 per person per day poverty line (Harrison et al, 2016, p.8). The same ODI report also estimates that 82% of SunnyMoney customers (SolarAid's social enterprise) buying the simplest solar-powered lights costing around US$10 live below the US$3.10 per person per day poverty line: 62% in Zambia, 73% in Tanzania, 85% in Kenya, 85% in Uganda, 99% in Malawi. The Acumen report shows that 36% of the customer base of five SHS and mini-grid companies across four East African companies lives below the poverty line at US$3.10 per person per day and it found that 82% of customers of a solar mini-grid PAYG service in Tanzania live below the US$3.10 per person per day poverty line (Harrison et al, 2017, p. 18).

Mini-grids, in particular mini-hydro and biomass systems, are the cheaper option measured in LCOEs, but only economical feasible in less dispersed populations and require additional capital in distribution wiring, metering, and monitoring, and also management of bill collection (Chattopadhyay, 2015, p.47). Affordability depends on how these costs are billed or paid for or not by the households.

Willingness to pay

The literature mentioned different factors that influence off-grid customers in their willingness to pay for pico-solar, SHS or mini-grid systems:

- **Extra connection fees and wiring costs**: for mini-grid or grid solutions connection fees and wiring costs add to the consumer price. For mini-grid and grid solutions these costs could be significantly high: up to US$400 (IRENA, 2016, p.53) in sub-Sahara Africa.
- **Demand fits supply**: Most of the off-grid household do not need Tier 5 high capacity electricity solutions, but are currently looking to set their first step on the energy ladder. Mini-grid and grid solutions are not flexible for different demands at the base of the pyramid, while a SHS can meet the demands of the household with easy options to upgrade their system. In the Acumen report (Harrison et al, 2017, p. 20) evidence is shown that for customers purchasing larger solar systems, there is a higher chance they would've previously experienced solar energy.
- **Ownership**: Costs for SHS seem high in comparison with the Watt and Watthour that it generates, but after a period of time the household owns the solar home system and the appliances (e.g. radio, lights, small TV) without having to make further payments. For a

pico-solar home system this could be in one year, while more advanced systems will take several years.

- **Financial services**: Households often buy pico-solar systems and SHS with PAYG or other micro-finance services, sometimes related to mobile money platforms like M-Pesa. This gives them the option to pay on a low daily or weekly-base (PwC, 2016, p.10). While testing small-scale trials for payment by instalment for solar products, SolarAid saw customers with lower incomes being able to access the solar lights, because families had access to the lights at minimal risk and cost (Harrison et al, 2017, p.18).
- **Reliability of the system**: grid solutions are not always reliable. Variable voltages can damage appliances and during blackouts a household needs to fall back on a back-up system. Pico-solar and SHS systems are reliable, especially with LED lighting, but depending heavily on quality of batteries (IEA, 2013, p.14).

Changes in spending after purchase

Most studies estimate rather than measure the savings after a family enters the energy ladder. Empirical evidence of financial savings is provided in a small number of studies. There is a reduction in expenditure on fuel (mainly kerosene), however, the literature measures this reduction differently. One study found a reduction of around 10-15% of the average weekly household income (Hassan et al, 2014, p.6). An evaluation conducted on a GIZ solar electrification project in Uganda found that households with SHS spent less than half per lumen hour than non-users (Harsdorff et al, 2009, p.77). A study in Rwanda found that households which were given pico-solar lights declined expenditure on kerosene by almost 70% followed by a decline in expenditure of dry-cell batteries and candles, followed by mobile phone charging costs (See table 2). The households paid one-fifth as much per hour of lighting as households without pico-solar lights, which paid 7 times more per lumen; showing the low quality of lighting of fuel-based options (Grimm et al., 2014, p.31).

Table 2: Price, consumption and total expenditures of lighting energy in rural Rwanda

Part 1. Price and consumption

	Households with pico-PV	Households without pico-PV	ITT	p-value
Cost per lighting hour (in FRW Per 100 hours)	176	950	-702	.000
Cost per lumen hour (in FRW Per 100 hours)	9	70	-57	.000
Lighting hours consumed per day	4.43	3.85	0.59	.074
Lumen hours consumed per day	142	61	78	.000

Part 2. Total expenditures:

Candles	42	109	-20	.339
Kerosene for lighting	155	609	-418	.000
Big batteries (Type D)	358	352	-9	.750
Small batteries (Type AA)	30	72	-43	.003
Mobile Phone charging	407	520	-68	.407
Total expenditures on these energy sources	993	1,662	-557	.000
Total household expenditures	37,971	31,334	7,249	.276
Share of energy expenditures on total expenditures	0.04	0.07	-0.03	.001

Source: Grimm et al, 2016, p.29 and p.30

The SolarAid market research (2012-15) across Kenya, Malawi, Tanzania, Uganda and Zambia found that after purchasing a solar light 71% of families reduced their lighting spending, primarily on kerosene (Harrison et al, 2016, p.9). Of those households which were using kerosene for lighting before purchasing a solar lantern, 69% eliminated kerosene use altogether. After solar light ownership, families saved US$60 a year, spending on average just 2% of their household income on lighting. These savings differed depending on the lighting source that was previously used (for example, kerosene lamps account for a higher weekly spend for families compared to candles) (Harrison et al, 2016, p.9). The savings were most pronounced in Kenya where households went from buying an estimated 9 litres of kerosene a month for lighting to 1 litre a month after adopting solar lighting.

The savings are large for pico-solar systems, but there is not a significant increase in relative savings for households using larger SHS. There is some evidence that larger systems reduce the replacement rate of traditional lighting less than portable solar lights, because large systems frequently power a fixed light, but not in all rooms, necessitating the continued use of kerosene in some cases (Harrison et al, 2016, p. 9).

There is some evidence to show that when lower-income households access larger systems, maintenance could become a problem, for example, if funds are not available for replacing batteries (IRENA, 2016, p.47; Harrison et al, 2016, p.10). Companies offering solar-as-a-service could take over the maintenance costs of bigger systems and spreading out costs for poor families. The Africa Progress Panel reports (2015, p.17) that halving the costs of inefficient lighting sources would save US$50 billion for people living below US$2.50 per day. It estimated that the monetary saving from cost reductions would be sufficient to reduce the poverty of 16-26 million people.

6. Benefits and externalities

Benefits of pico-solar systems and SHS

The literature shows that the benefits of pico-solar lights and SHS go beyond the financial savings, in particular for low density populations that want to take the first step on the energy ladder. For example, UNEP (2013) estimated that pico-solar systems increased the number of hours that lights are used by about 1 hour a day to a total of 5 hours. Mentioned benefits include:

- **Productive work-hours at home**: 11% of pico-solar light users interviewed by SolarAid (2012-15) reported using their solar light for business use, including using it for neighbours to charge their phones for a small fee. Of these 98% said it had positively affected their hours of business, and 76% said it had positively affected how their customers interacted with their business (Harrison et al, 2016, p.11).
- **Opportunities for women**: 41 percent of (globally) surveyed women report having increased income and professional opportunities once they own a phone, particularly women in rural areas or with low incomes. Therefore, the benefits of modern lighting are multiplied when multifunctional lighting devices also empower women to access modern communication services more easily (Alstone et al, 2011, p.14). 80% of women from households with SHS in Uganda did domestic work in the evenings after sunset (for 2.2 hours, on average), whereas only 66% of those without SHS did (for 1.9 hours). 27% of women specifically said they used the SHS to complete their household chores after sunset (Harsdorff et al., 2009, p.58) and that gives women opportunities to do more paid-work during the day. Acumen's data suggests an average of 3.5 hours saved per month from avoiding going to market to purchase kerosene, batteries or candles, something that is mainly a job for the women (Harrison et al, 2017, p.64).
- **Education**: The GIZ study found that the main beneficiaries of the SHS were children (53%), who used them to complete their homework at night (Harsdorff et al., 2009, p.60). SolarAid research shows that children increased their study hours by more than an hour per night after accessing a pico-solar light. Acumen's data supports this pattern seeing increases of evening study hours for children on average at 1.0, 0.8, and 0.4 across three different companies (Harrison et al, 2017, p.64). Electricity can also improve schools through better lighting; the use of fans to control temperature; more efficient administration through computers and other ICTs (Harrison et al, 2016, p. 16)
- **Health**: While household air pollution resulting from cook stoves has been extensively studied in the literature, particulate concentrations from fuel-based lighting have received less attention. It has been known that kerosene-using devices emit substantial amounts of fine particulates, carbon monoxide (CO), nitric oxides (NOx), and sulphur dioxide (SO2) (Lam et al., 2012, p.1). Studies on kerosene used for cooking or lighting provide some evidence that their emissions may impair lung function and increase infectious illness (including tuberculosis), asthma, and the risk of cancer. The World Health Organisation's (WHO) Guidelines for Indoor Air Quality (2014, p.15) state that existing evidence shows that household use of kerosene can lead to unhealthy levels that exceed the guidelines. Poisoning also often occurs as kerosene is commonly sold in soda bottles and it can be mistaken for soda (WHO, 2014, p.15). UNICEF (2015, p.12) report that the

primary cause of child poisoning in developing countries is accidental kerosene ingestion, and burns are identified as one of the leading causes of child injury. A shift to solar solutions suggests a reduction in the amount of accidents caused by kerosene.

- **Nutrition and wellbeing**: Savings on lighting expenditures are reportedly spend on food for a better balanced diet and nutrition intake (Harrison et al, 2016, p.18). In surveys solar lighting users talk about the opportunity to spend more time together as a family, invite friends, eat together and share experiences. All SHS user respondents of a study in Bangladesh agreed that SHS increased their time spent in relaxation and their ability to get together at night and enjoy the high quality light (Urmee et al, 2011, p.2825). 85% of pico-solar light users across sub-Sahara Africa said that having a solar light affected the activities they were able to do at night (Harrison et al, 2016, p.19). There is an important difference between pico-solar light and SHS. A SHS offers fixed ambient light with no portability, a pico-solar light is often more of a directed task light; this may change behaviour and usage, particularly when reflecting on who in the household has access to the lighting (Harrison et al, 2017, p. 31).
- **Environment**: Estimates of greenhouse gas emissions from kerosene lighting vary with the assumptions used in their calculation. UNEP (2013) estimates that the substitution of solar lighting for all traditional lighting would save about 34 million tons CO2 a year. For individual households in Bangladesh it was found that SHS users reduced their emissions by 95.3kg of CO2 per year, while smaller SHS users reduced CO2 emissions by 68.3kg per year (Brossman, 2013, p.64). The ODI report estimates a total emission saving from sales of solar lights in Africa over the period 2011 and 2014 to be 757,000 tons a year (Harrison et al, 2016, p. 17). A further 270,000 tons of black carbon per year are estimated to be emitted from kerosene lamps worldwide (Lam et al, 2012, p.13535). And climate forcing from households using kerosene lighting is nearly 10 times as high as that of the typical grid-connected household in Kenya (Alstrone et al, 2015, p.312). The decline in dry-cell batteries use to power lighting and radio is also a positive effect, although all solar household systems depend on larger batteries. The concern is lack of awareness among populations on the environmental impact of battery disposal (Harrison et al, 2016, p. 17).
- **Access to ICTs**: For the solar systems that provide lighting and mobile-phone charging, there are additional impacts. 95% of SHS users in Bangladesh reported that their access to information and services (e.g. financial, agricultural apps) through mobile phone, TV or radio had been improved by their SHS (Urmee et al, 2011, p.2825). A study in Uganda found that 86% of microenterprises who had invested in a SHS used mobile phones for their work whereas only 62% of the non-users did (Harsdorff et al, 2009, p.57). SolarAid (2012-15) data shows that pico-solar households in Kenya, Malawi, Tanzania, Uganda, and Zambia reduced their average US$0.94 each week spending to power their radio prior to a solar light purchase to no costs (Harrison et al, 2016, p.18). Harsdorff et al. (2009) also found that SHS owners in Uganda spent less on radio charging too.
- **Jobs and entrepreneurship**: Up to 15,000 new jobs have been created in the wider economy in sub-Saharan Africa as a result of the transition to efficient off-grid lighting (UNEP, 2014, p.3). Renewable and efficient energy create many times more jobs than non-renewable energy systems do, particularly for non-oil producing countries. In Bangladesh alone, the Africa Progress Panel (2015) found that 10 years ago there were an estimated 25,000 small solar systems in the country. There are now 3.5 million and it is estimated that the boom has created around 114,000 jobs in solar panel assembly. A related issue is the traditional role of the kerosene vendor. Rather than trying to put them

out of business, it should be preferred to involve them in the business of selling modern lighting systems (IEA, 2012, p.13).

- **Innovation and development**: The combination of more and better light, access to ICTs and awareness of solar technology increases opportunities of marketing new services and technologies to off-grid populations. Entrepreneurs enter the market with special applications for mobile phones, SMS-services and solar enabled technologies (e.g. solar PV irrigation pumps, solar PV cool storage, solar PV food dryers), with the potential to increase economic development and output (IRENA, 2016, p. 61).

Benefits and risks of mini-grid systems

Success of mini-grid systems depends on the technology – hydro, biomass, solar PV, diesel, hybrid - the geographical location, management skills and ownership model (Hazelton et al, 2014, p. 223; World Bank, 2016, p.17). The literature mainly focusses on the benefits and risks of shifting from diesel generated mini-grids to renewable sources or hybrid systems.

The literature mentions the following benefits:

- With the increase in renewables, a reduced need for the diesel generator will mean the run hours of the generator will accrue at a lower rate. Also, by not being required to service low loads the generator lifetime (run hours to failure) would increase (ARE/USAID, 2011, p.31; Hazelton et al, 2014, p.225).
- A reduced need for diesel also means reduced reliance on an often uncertain supply-chain, and volatile commodity prices, and can benefit service reliability as well as reduce price risk (Dekker, 2014, 109).
- For Tier 3 situations it has been assumed that hydro and renewable mini-grids increase willingness to pay due to improvement to electrical services and increased reliability (in comparison with diesel only mini-grids) to power high electricity consuming equipment for less LCOEs. Users pay only for the amount of consumed energy (Hazelton et al, 2014, p.225)
- Mini-grids give opportunities for rural enterprise that need the next step on the energy ladder (Tier 2/3/4) mini-grids have the benefits over SHS as the latter is unable to service larger loads (ARE/USAID, 2011, p.32; Hazelton et al, 2014, p.225).
- Like the solar household systems, renewables for mini-grid systems have significant environmental benefits, less air pollution and CO2 reduction (Hazelton et al, 2014, p.225)
- Mini-grid systems are better equipped to serve community centres, schools, small hospitals and communication base towers, improving livelihoods not only on household level but for whole communities (Hazelton et al, 2014, p. 225).
- Models of community ownership have been developed whereby the end users are also the owners and operators of the system, this ensures incentives are aligned and contributes to the development of the whole community (ARE/USAID, 2011, p.21).
- The long term advantage of mini-grid systems is that they can be integrated within grid extension projects (World Bank, 2016, p. 16).

The literature mentioned the following risks:

- Many mini-grids have been government-or donor-led and rely on some form of subsidy and the continuing commitment of the sponsoring agency, which brings in some uncertainties for sustainability (World Bank, 2016, p. 16).
- The success of mini-grid programmes depends on a broader energy development strategy, including the role of stand-alone solutions and grid connection. Any long term uncertainty makes the private sector less interested in mini-grid extension or upscaling (Chattopadhyay et al, 2015, p.44).
- Better planning and a detailed local energy-sector mapping is required to identify the most cost-efficient route in particular locations. This is particularly the case in Africa, where grid extension is limited due to substantial distances across the continent and the cost and losses related to this (Hazelton et al, 2014, p.227).
- Mini-grid is not suited for a highly dispersed population (Nerini et al, 2016, p.257).
- It needs efficient additional capital in distribution, wiring, metering, and monitoring, and requires management of bill collection (Chattopadhyay et al, 2015, p.44).
- Mini-grids operate on AC and much higher voltages relative to solar home systems, so risks of harm to operators and users is increased. Extensive wiring throughout communities may present dangers not well understood (Hazelton et al, 2014, p.227).
- System failures are expensive and especially in remote areas take more time and money to solve. A failure affects the whole community (ARE/USAID, 2011, p.21; Hazelton et al, 2014, p.226).
- To operate and maintain the system is more complicated and in particular batteries for storage are vulnerable and need good maintenance (IRENA, 2016, p.47).

7. Future developments

In recent years pico-solar light systems have been reduced in costs and are sold in Africa for under US$10. The literature does not expect such a rapid fall in pico-solar lighting systems to continue, but the focus to shift onto better quality within the same price margins. With **kerosene prices expected to increase**, poor households could continue to turn to pico-solar solutions (Altone et al, 2015, p.312).

For SHS the literature estimates a further cost reduction, which would make them become more interesting for the poorest households. The IRENA report (2016, p. 55) shows that **for a medium SHS a cost reduction of around 68% could be possible**. Most of the cost reduction is estimated to come from the reduction in hardware costs (24% reduction), also significant cost reduction could be made on battery costs (14%) and soft costs (14%). Module cost (part of hardware costs) could fall between US$0.28 and US$0.46/W (see more in appendix).

In the near **future lead-acid batteries battery technologies could see a significant reduction in costs**. However, the high quality lithium-ion batteries, which perform much better, will to a lesser extent reduce in cost price. Li-ion batteries have a longer battery life and can operate at much higher depth of discharge rates with reducing battery lifetimes. If being introduced in Africa li-ion batteries will raise initial instalment costs, but will result in a lower LCOE over the life of the system and also significantly extend the time between battery replacements, helping to improve the probability that systems will remain active over their economic lifetime (IRENA, 2016, p.55).

Swarm electrification will become a new option for SHS. This means that **stand-alone systems could be scaled up and connected to each other** to create a diverse local or even regional grid that eventually could be connected to the central grid (Lucas et al, 2017, p.45).

Mini-grid solutions will revive as renewable solutions continue to reduce in costs and **demand for electricity is expected to increase in sub-Sahara Africa** (IEA, 2014, p.29). The World Bank signals a **learning curve on mini-grid programmes and knowledge sharing**. Countries in Africa, like Rwanda and Kenya, are willing to learn from programmes in Asia (India, Sri Lanka and Bangladesh) and have mainstreamed planning, programmatic financing and implementation of comprehensive and coordinated grid and off-grid rollout programmes to systematically scale-up towards universal access (World Bank, 2016, p.21).

Although less research has been done on other renewable technologies than solar PV systems for mini-grids, it is expected that **biomass, wind and hydro technologies also reduce in price while improving in quality** - to become competitive alternatives for solar PV and diesel in specific geographical locations (Nerini et al, 2016, p.260).

Future price estimates need to consider import and excise duties, value-added tax, and surcharges that all affect the end price consumers pay. It is expected that **renewable energy systems will be taxed on a low rate, while diesel could become more expensive as it some governments will lower high diesel subsidies** (PwC, 2016, p.12).

Connecting the energy poor to electricity is just a first step. Giving them the ability to do something with that power, needs energy efficient appliances, in particular in refrigeration. It is expected that **new technologies will make appliances more energy efficient.**

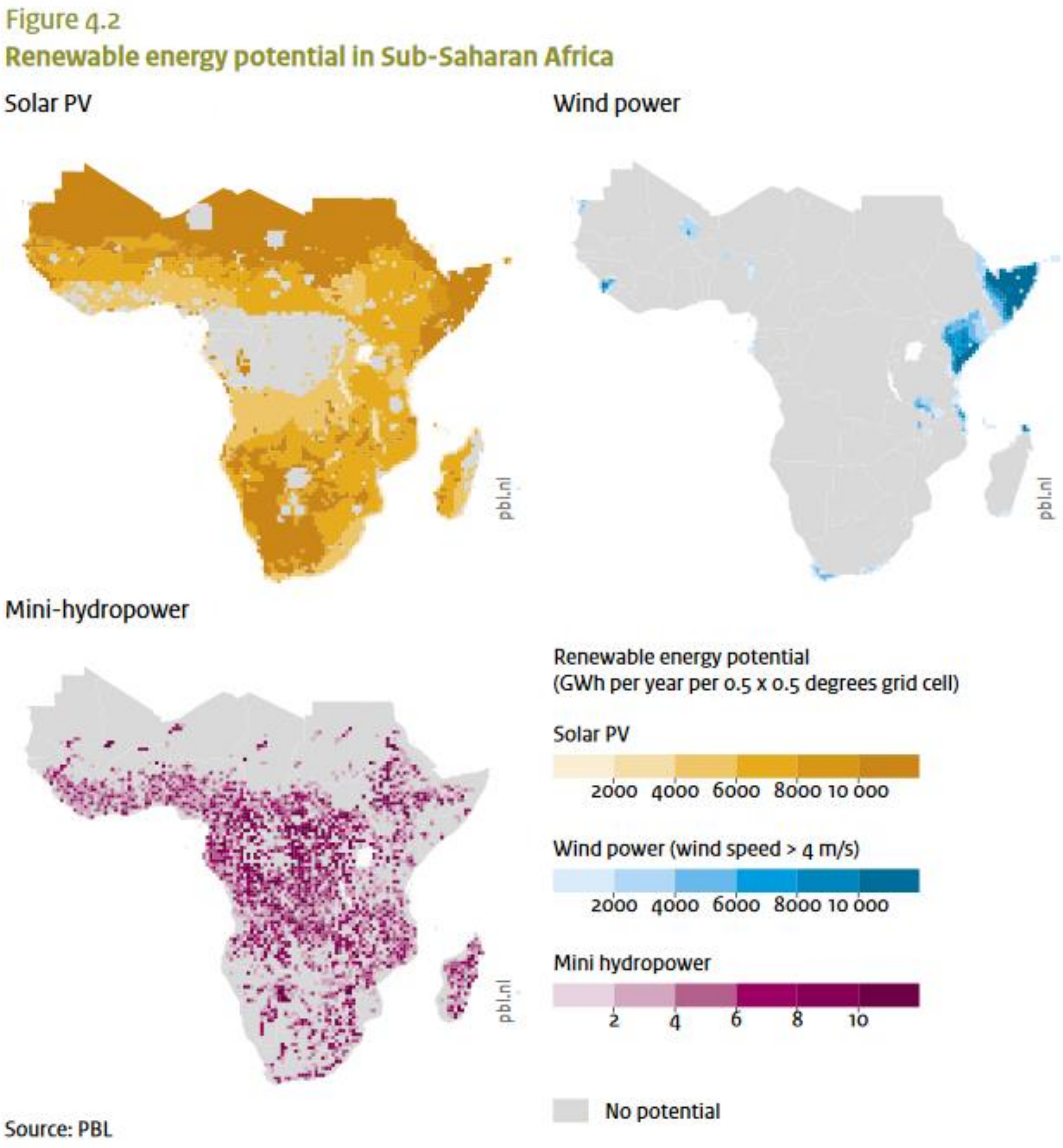
Data analytics is another game changer that is playing an increasingly significant role. PAYG companies are **using real-time data feeds from installations** to analyse usage and payment patterns. This data is also allowing them to anticipate repair and maintenance requirements. Using data analytics could further help in identifying the best sites for standalone solutions, mini-grids and national grid extension (PwC, 2016, p.17).

Bottom-up customer demand is proving to become more important and businesses are looking to new ways and business models to meet demand with stand-alone or mini-grid solutions. **Business models are expected to transform into more connected smart off-grid energy systems with a substantially larger market size compared to those today**. New business models driven by the development of mobile payment, data analytics and large battery systems will emerge and drive the transformation (PWC, 2016, p. 17).

Following the establishment of SDG7 (Ensure access to affordable, reliable, sustainable and modern energy for all), there will be a focus by international groups, foundations and NGOs in the energy sector for the years to come.

8. Appendix

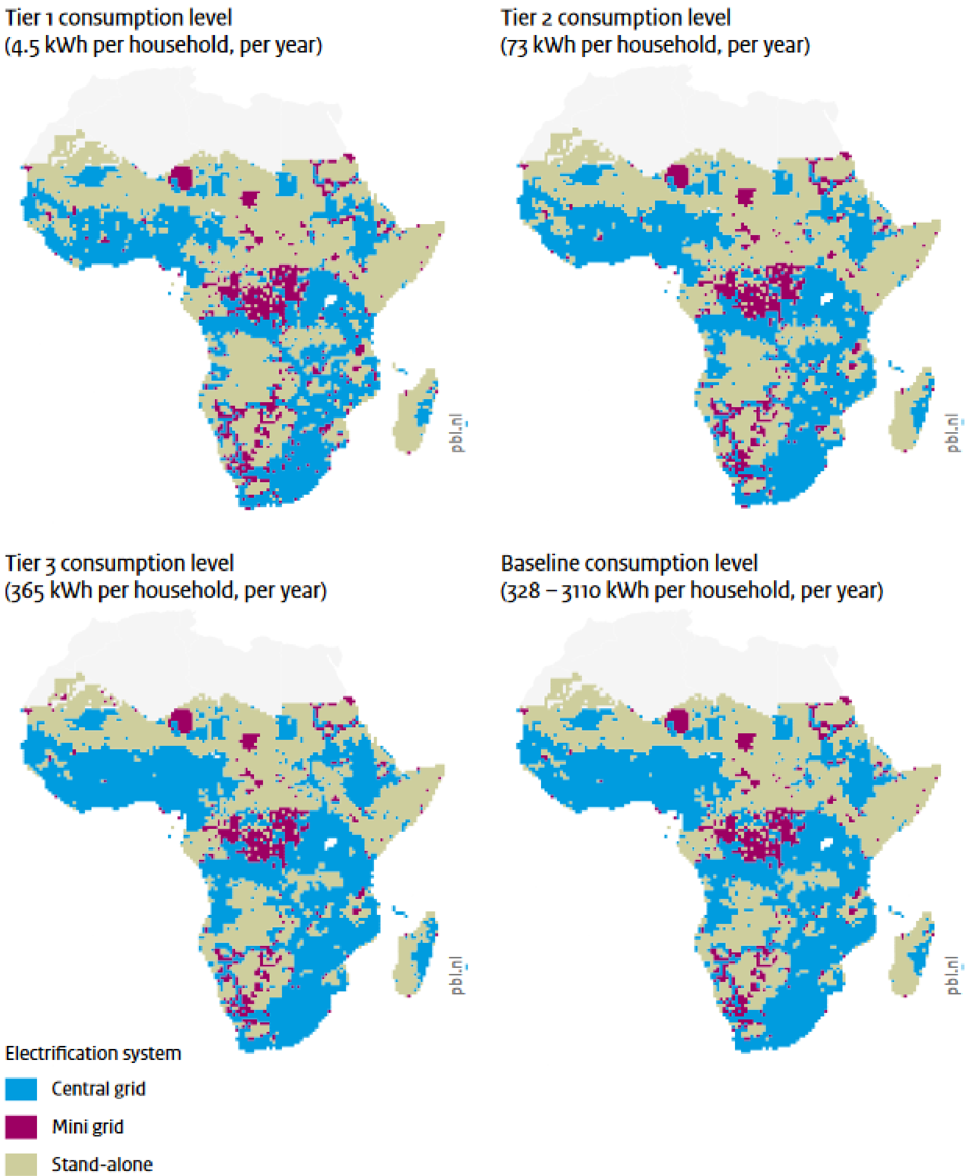
Figures from the literature on mapping sub-Sahara Africa



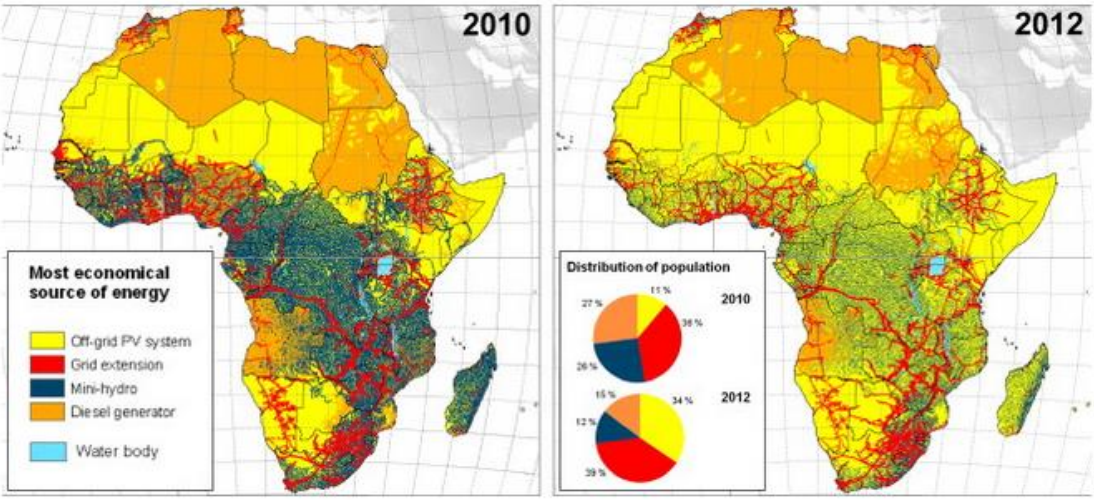
Source: Lucas et al, 2017, p.34

Figure 4.4

Least-cost electrification systems under SSP2 baseline scenario with universal electricity access, 2030



Source: Lucas et al, 2017, P37

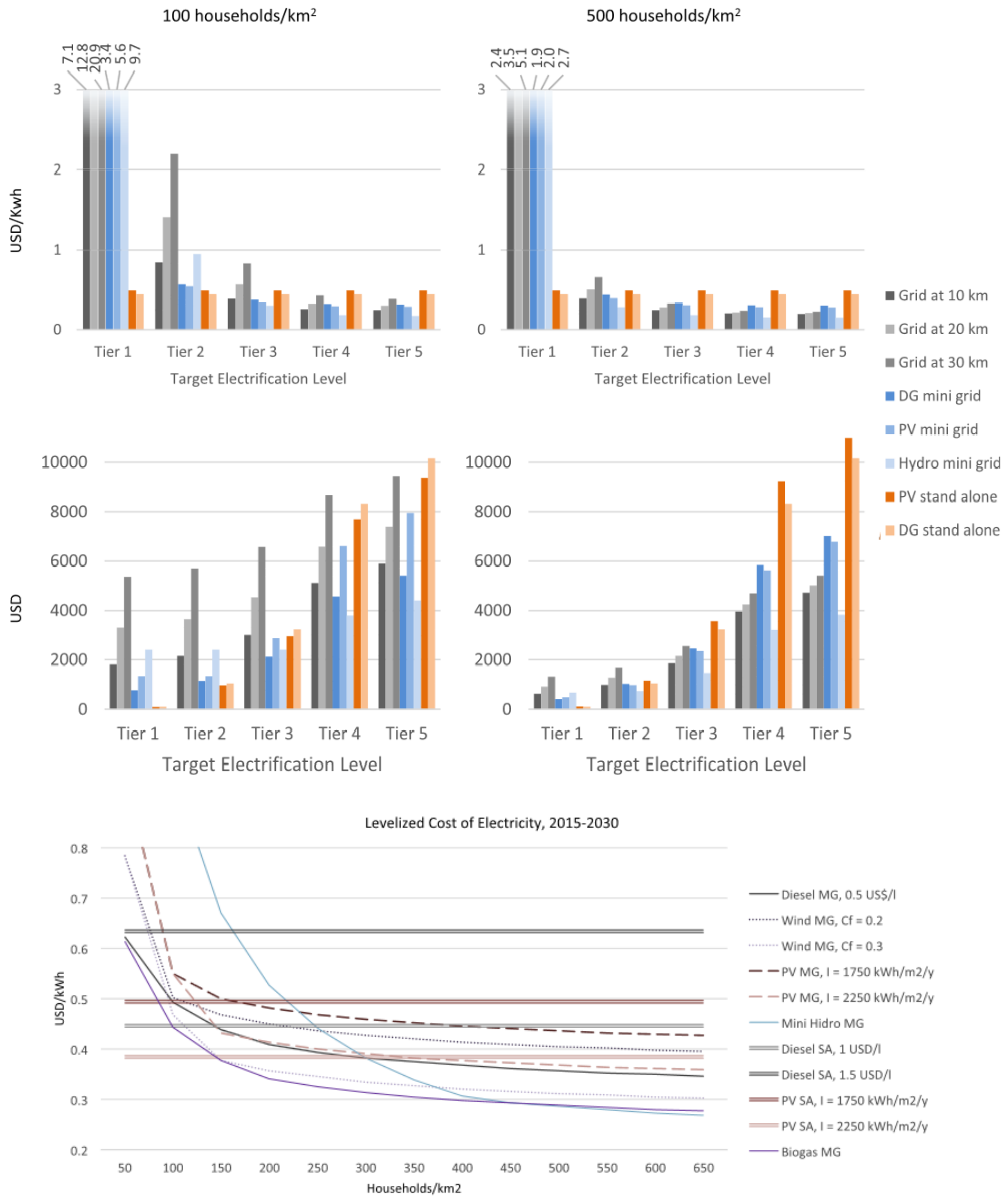


Download full-size image

Fig. 9. Regions where grid extension may prove to be the most economic option (reddish lines) are limited to high population density regions close to the already existing grid. But overall, distributed power generation (shown in yellow for PV, orange for diesel gensets, and blue for mini hydro) – as contrasted to grid extension – is a more viable option for many communities in vast regions of Africa. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

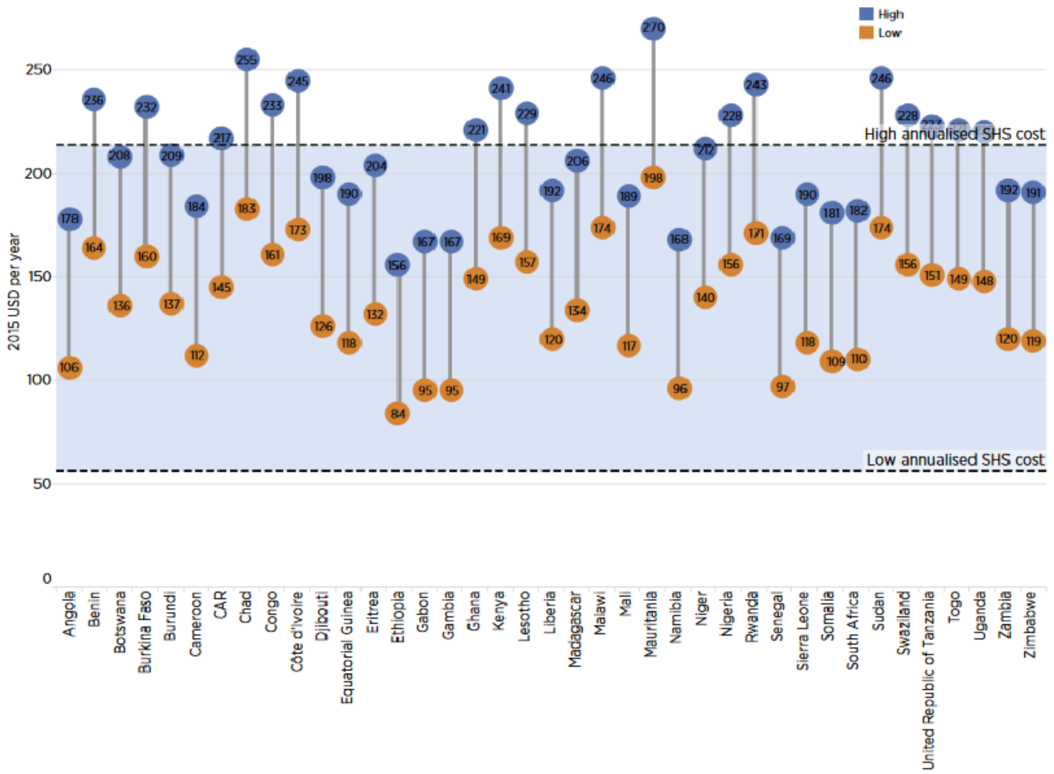
Source: Szabó et al, 2013, p.507

Figures from the literature on cost comparison



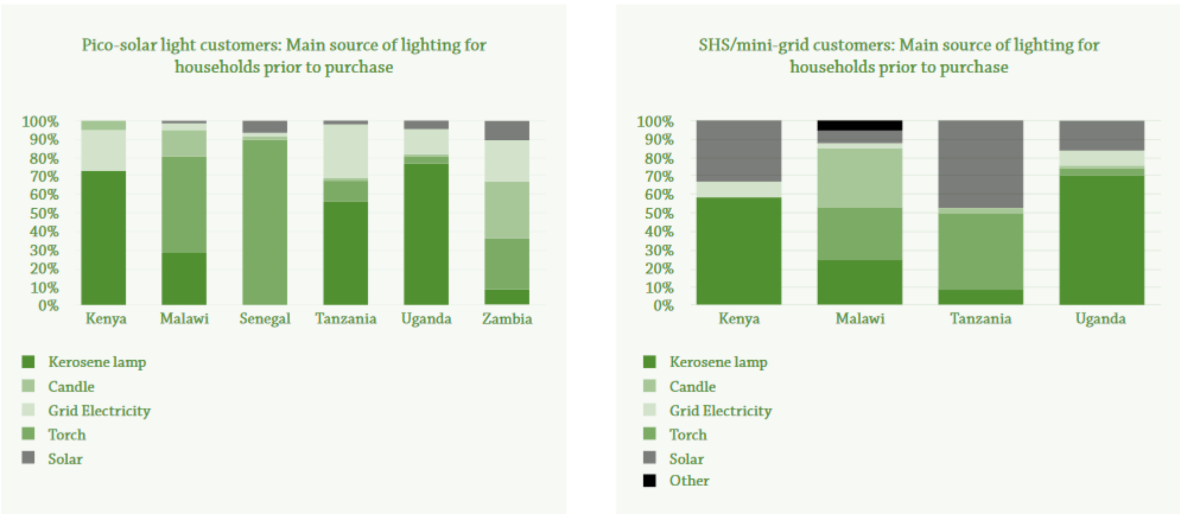
Source: Nerini et al, 2016, p.259

FIGURE ES 2: ANNUAL OFF-GRID HOUSEHOLD EXPENDITURE ON LIGHTING AND MOBILE PHONE CHARGING COMPARED TO SHS (< 1 kW) ANNUALISED COSTS, BY COUNTRY IN 2015



Note: The blue band represents the range of annualised SHS costs, while the circles represent the high and low annual expenditures of off-grid households for lighting (e.g., kerosene, batteries, candles, etc.) and mobile phone charging.

Source: IRENA, 2016, p.47



Source: Harrison, 2017, p.20

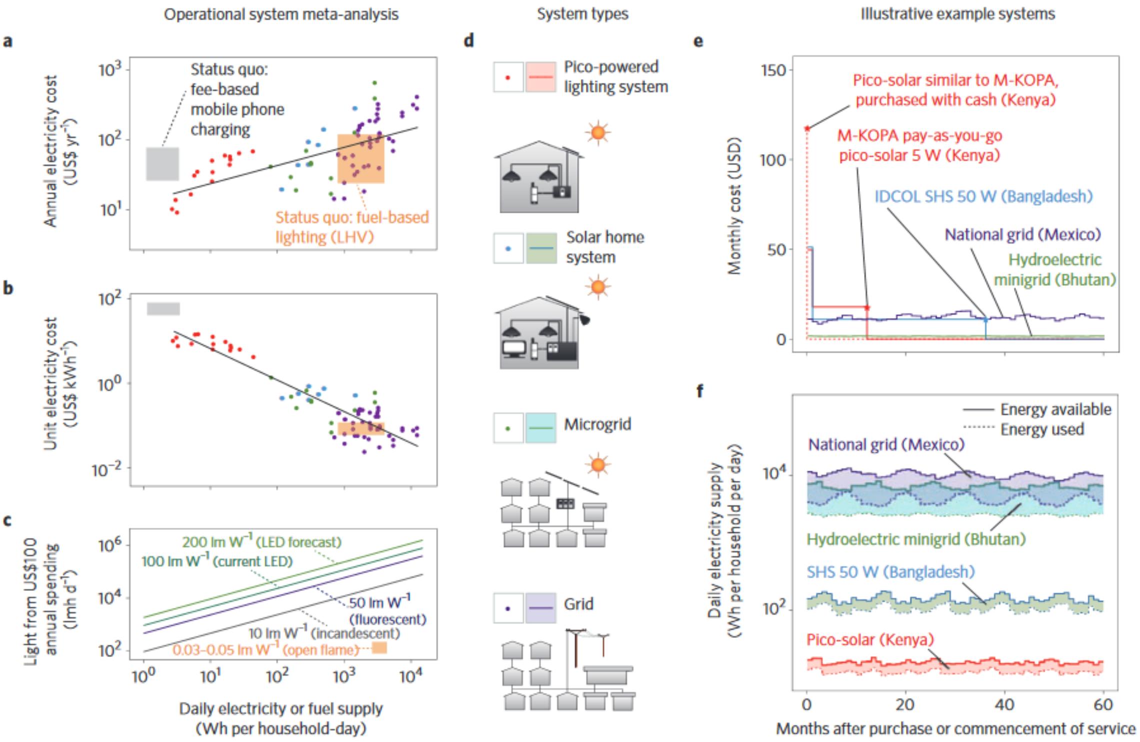


Figure 4 | Five views on the continuum of electricity access based on real-world system operations. a,**b**, The annual (**a**) and unit (**b**) costs of electricity. The incumbent options (fuel-based lighting and fee-based charging) are included for reference, with fuel-based lighting in terms of lower 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.

Source: Alstone et al, 2015, p.310

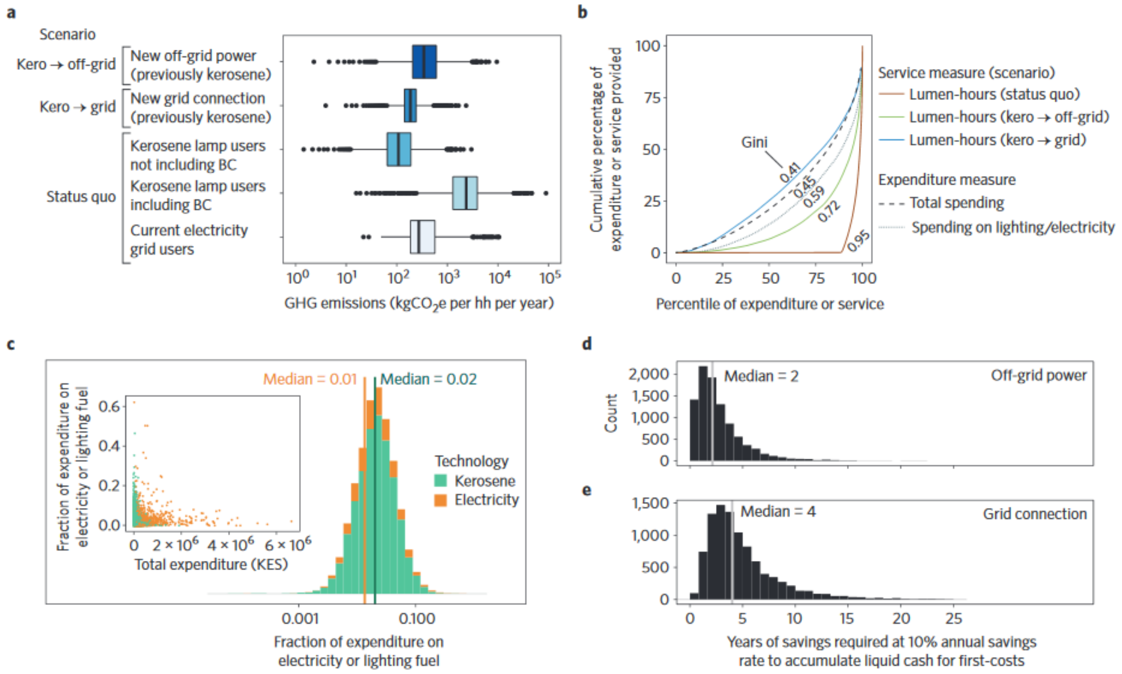
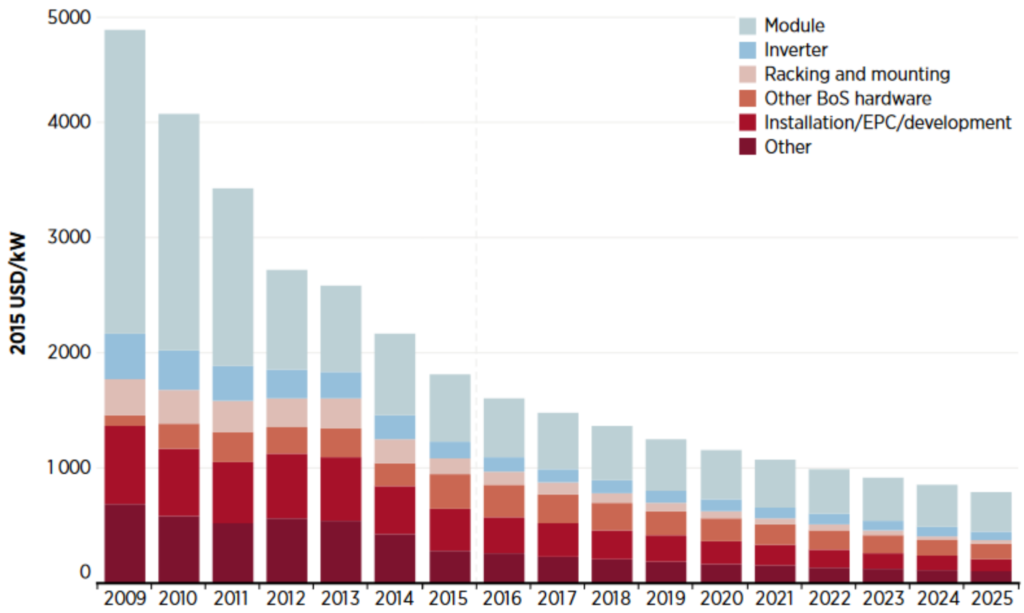


Figure 6 | Results from a simple model of climate impacts and adoption dynamics for electricity and lighting technology in Kenya. The base data are from the Kenya National Bureau of Statistics (KIHBS 2005/06, $n = 13{,}430$). **a**, Expected range in GHG emissions induced by household (hh) electricity 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).

Source: Alstone et al, 2015, p.312

Figures from the literature on future trends

FIGURE 12: GLOBAL WEIGHTED AVERAGE UTILITY-SCALE INSTALLED SOLAR PV SYSTEM COSTS AND BREAKDOWN, 2009-2025



Source: IRENA analysis and Photon Consulting, 2016

Source: IRENA, 2016, p.36

Table A. 1
Electricity generation technology parameters used in the model, BC scenario; The capital cost for the first year of the projection was calculated with the most reliable source for small scale technologies, and checked with other sources as indicated below. Cost projections are selected according to the IEA New Policies Scenario recommendations [17]. Sources [13,14,25,26].

Plant type	Investment cost 2015 ($/kW)	Investment cost 2020 ($/kW)	Investment cost 2030 ($/kW)	O&M costs (% of investment cost/ year)	Efficiency	Life (years)
Diesel Genset – Minigrid	721	721	721	10%	33%	15
Mini Hydro – Minigrid	5000	4896	4751	2%	–	30
Solar PV – Minigrid	5000	4341	3547	2%	–	20
Wind Turbines – Minigrid	3631	3523	3318	2%	–	20
Biogas Genset – Minigrid	1252	1324	1324	10%	33%	15
Diesel Genset – Stand Alone	938	938	938	10%	28%	10
Solar PV – Stand Alone	6000	5209	4256	2%	–	15

Source: Nerini et al, 2016, p.261

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