nature energy

SUPPLEMENTARY INFORMATION

https://doi.org/10.1038/s41560-018-0240-y

In the format provided by the authors and unedited.

The cost of reliability in decentralized solar power systems in sub-Saharan Africa

Jonathan T. Lee and Duncan S. Callaway*

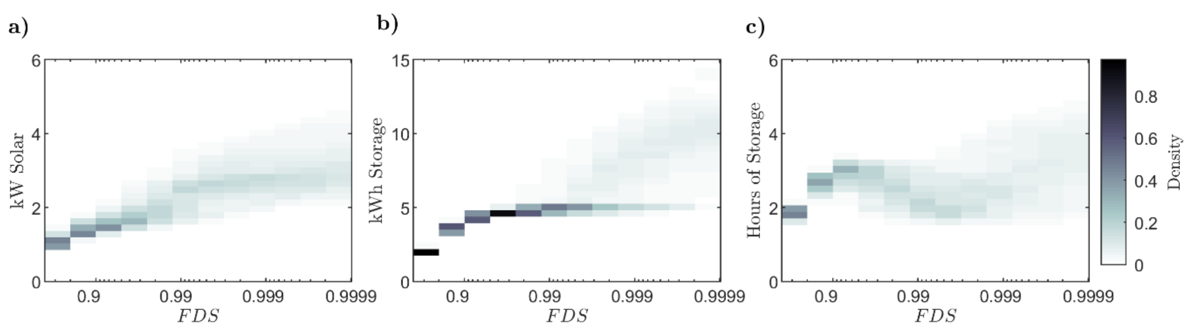
Energy and Resources Group University of California, Berkeley, CA, USA. *e-mail: dcal@berkeley.edu

Supplementary information: The cost of reliability in decentralized solar power systems in sub-Saharan Africa

Jonathan Lee and Duncan Callaway*
Energy and Resources Group
University of California, Berkeley

Supplementary Note 1

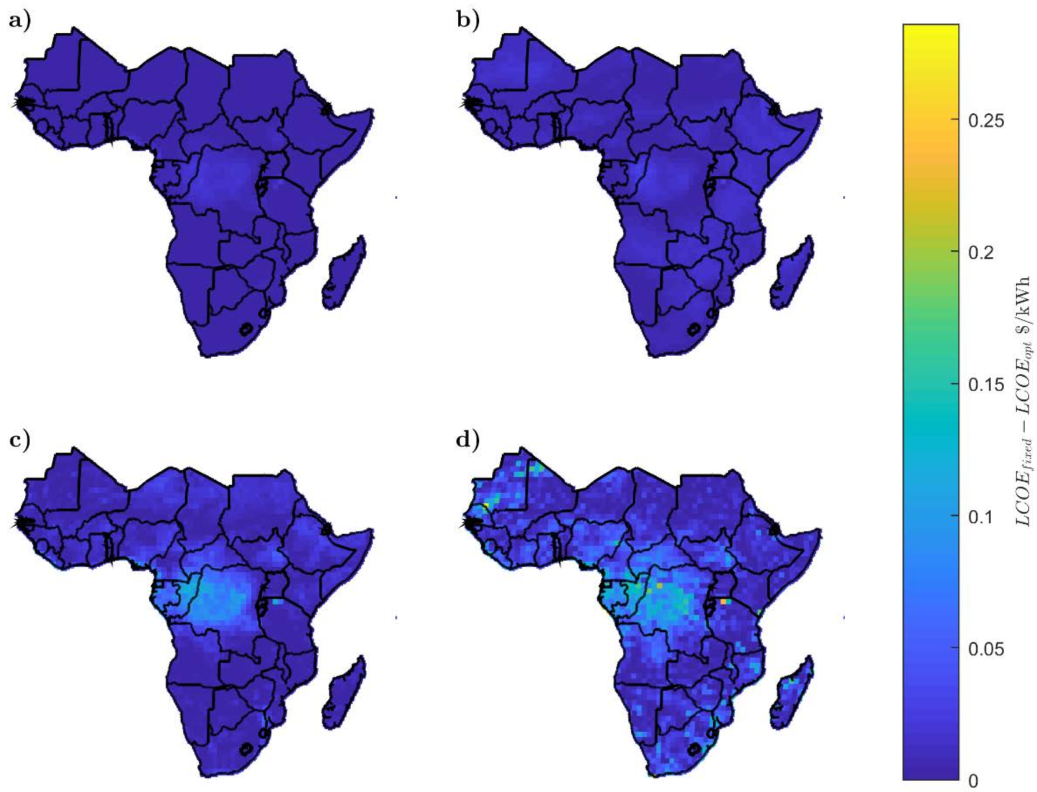
Supplementary Figure 1 shows the range of optimal system designs – that is, the lowest cost capacities of solar and storage that ensure a given FDS – for ESMAP Tier 5 systems across each location as FDS changes. There is wide variation in the storage to solar ratio at high FDS, and though solar capacity increases fairly regularly with FDS, storage capacity does not increase much from 90% to 99% FDS, causing the ratio to decrease in this range of FDS. At FDS above 99%, storage capacity takes a bimodal distribution, causing the storage to solar ratio to scatter nearly uniformly between 2 and 4 hours from 99.9% to 99.99% FDS. The key results from Supplementary Figure 1 are that optimal system design is more variable at higher levels of reliability, which implies that considering how the optimal system design changes with location is especially important at high levels of reliability, and is consistent with Figure 5 of the main text and Supplementary Figure 2. We find also that the optimal storage to solar ratio is mostly confined to between 2 and 4 kWh of storage for every kW of solar, though this range is dependent on the shape of daily electricity load profile (see Supplemental Information). We note that this recommends a higher storage capacity than is reported by Levin and Thomas in a survey of installed SHS, who find most SHS use a ratio in the range of 1 to 2 kWh of storage per kW solar[1].



Supplementary Figure 1: Statistical relationship between optimal system design and FDS for Tier 5 systems at current costs. *Panel **a)** shows the density of the optimal solar capacity at different FDS for each location, while panel **b)** and **c)** show the density of optimal storage capacity and the ratio of storage to solar capacity at optimum.*

When repeating this analysis for the possible future cost scenario with factor of 4 reductions in battery costs and factor of 2 reductions in solar costs, there is a shift to higher storage capacity deployment. This shift in optimal system design as costs change will be important to include in multi-year planning tools that forecast changing prices of materials; i.e. it is not appropriate to assume that future systems will employ the same capacities of solar and storage. These results are also of practical importance to project developers and system designers in industry who must select the optimal system design to be built.

We have shown that there is wide variation in optimal system design at high FDS. We now examine the impact of choosing a suboptimal system design on costs to support the use of our more detailed model. To do this, we draw on the approach used by Szabó et al[2], where we calculate the optimal system design at each location for 95% FDS given current costs. We then hold that storage to solar ratio fixed, and calculate the solar capacity and resulting LCOE necessary to achieve different FDS using the fixed ratio. Thus, we can calculate the difference in cost between the optimal choice and the fixed ratio solution for each location (Supplementary Figure 2). The additional cost, or penalty for the sub-optimal solution, increases with FDS, and the spatial variation is significant. At FDS at or exceeding 99.9%, there is a cost penalty around USD 0.10/kWh in many regions if a suboptimal system design is used. From these results we conclude that it is appropriate to use a simple model for estimating the cost of decentralized systems at FDS below 99%, but at higher FDS, it is necessary to use an optimization that accounts for local weather patterns on a daily scale.

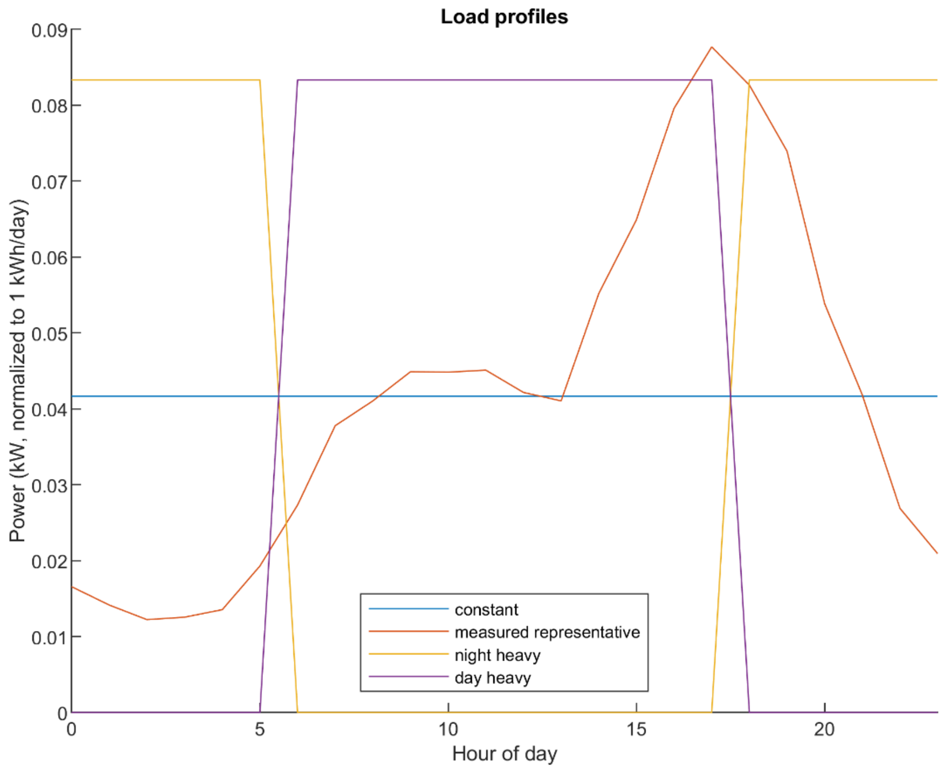


Supplementary Figure 2: Additional cost incurred if holding the storage to solar ratio fixed. *Panels **a)**, **b)**, **c)**, **d)** show the difference for FDS of 0.9, 0.99, 0.999, and 0.9999, respectively.*

Supplementary Note 2

As mentioned in the main text, the isoreliability curve is dependent upon the shape of the daily electric load profile: the shape of the load profile is part of the simulation to ensure that a particular system satisfies the target FDS. In the analysis presented in the main text, we use the simple assumption of a constant load profile. Ideally, we would have large datasets of electricity consumption across locations in SSA, but this is not available. Therefore, to test the robustness of our results we compare different load profiles. We find that having more demand at night increases LCOE due to additional storage capacity required, but that the logarithmic scaling and cost of incremental FDS are unchanged.

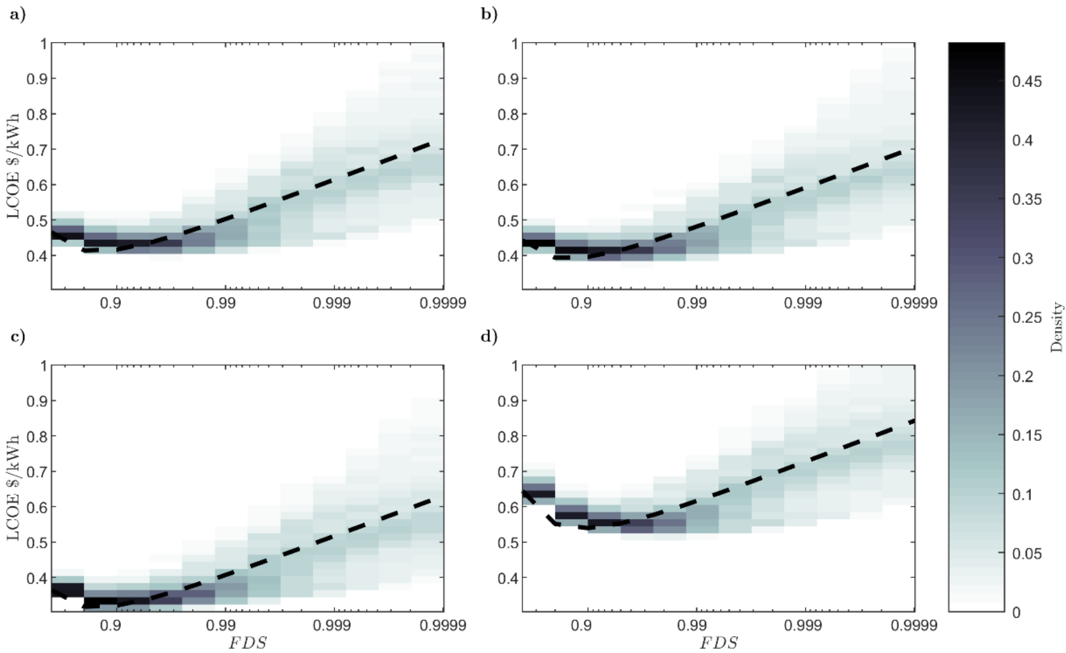
We compare four different load profiles: constant, day-heavy, night-heavy, and an empirical sample from a microgrid in Uganda shared by New Sun Road, Public Benefit Corporation. The shapes of the different load profiles are shown in Supplementary Figure 3.



Supplementary Figure 3: Daily load profile shapes

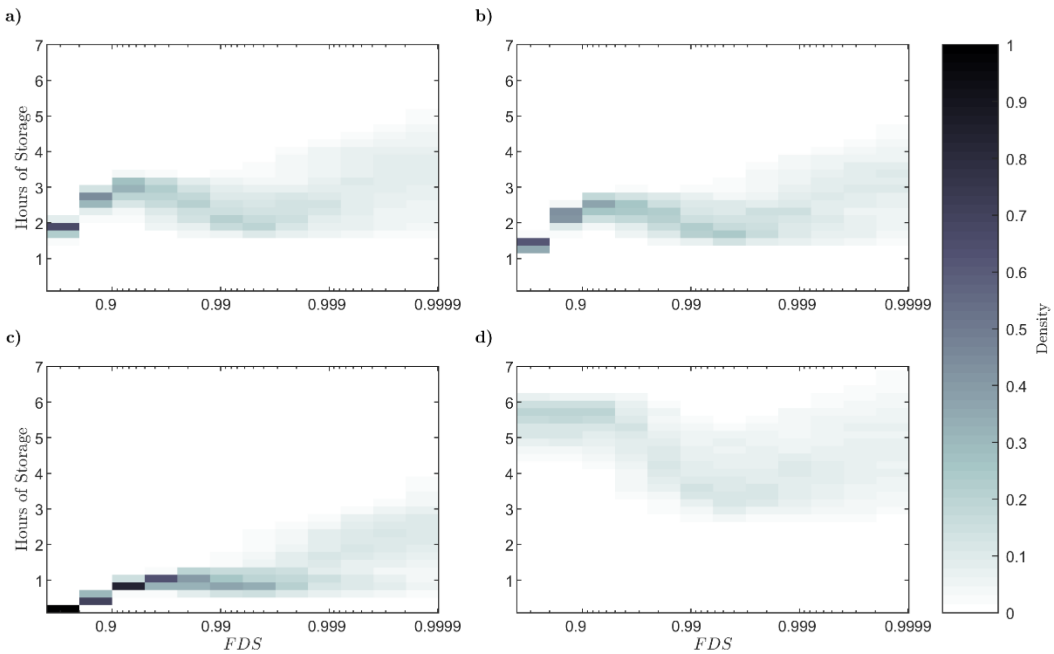
We compare the relationship between FDS and LCOE for different load profiles in Supplementary Figure 4. Demand concentrated during the day causes lower LCOE for the same FDS, while demand concentrated at night causes higher LCOE; however, the shape of the reliability premium and variance around the best-fit line are approximately the same in all cases. From this we conclude that changes in the daily load profile shift the LCOE by an amount that is independent of FDS.

It is also interesting to note that the constant demand assumption yields very similar results to the empirical load profile, which has a spike in the evening and low demand in the pre-dawn hours. This supports the use of the constant demand assumption in our analysis. In Supplementary Figure 4, we see a difference of approximately USD 0.25/kWh between the day-heavy and night-heavy scenarios. This can roughly be interpreted as an upper bound on the benefits that could be realized by shifting load from the night to the day through demand-response type programs. It is important to observe in Supplementary Figure 4 that the constant and sample measured demand have approximately identical costs. This is because the sample demand has an evening peak that is approximately balanced out by low consumption late at night, resulting in approximately the same amount of battery capacity necessary as the constant case. This similarity in results validates the assumption of constant demand used in the main text. It is also important to point out that the inverter capacity is specified by the ESMAP Tier 5 requirements[3], and is not dependent on the shape of the load profile.



Supplementary Figure 4: Statistical relationship of LCOE and FDS for different load profiles*. The plots show the density of computed LCOE at different FDS for each location in SSA sampled at 1 degree, as in Figure 3 of the main text. Panels* ***a)****,* ***b)****,* ***c)****, and* ***d)*** *show the relationship for the constant, measured representative, day heavy, and night heavy load profiles of Supplementary Figure 3, respectively. Note that panel* ***a)*** *is identical to Figure 3, panel* ***a)****, of the main text on a different vertical axis.*

We see in Supplementary Figure 5 that the demand profile affects the optimal storage to solar ratio. Unsurprisingly, having more demand at night requires more storage capacity relative to solar. In the case where all demand is at night, the optimal ratio is in the range of 3 to 5 hours of storage.



Supplementary Figure 5: Statistical relationship between optimal storage to solar ratio and FDS for different load profiles for Tier 5 systems at current cost*. Panels* ***a)****,* ***b)****,* ***c)****, and* ***d)*** *show the relationship for the constant, measured representative, day heavy, and night heavy load profiles of Supplementary Figure 3, respectively. Note that panel* ***a)*** *is identical to panel* ***c)*** *of Supplementary Figure 1.*

Supplementary Note 3

The data used in the main text for the electricity tariffs, reliability, and electrification are shown in Supplementary Table 1. Electricity tariff data was made available through a World Bank report[4], and at the time of writing can be accessed online at http://databank.worldbank.org/data/download/avpfa/avpfa-tariff.xlsx. For comparison to ESMAP Tier 5 systems, the tariff at 250 kWh per month was used as it corresponds to approximately 8 kWh per day, which is closest to the ESMAP Tier 5 requirement of 8.2 kWh per day of consumption. Reliability data was computed from the World Bank Enterprise Infrastructure Surveys[5], which at the time of writing can be viewed at http://www.enterprisesurveys.org/data/exploretopics/infrastructure#sub-saharan-africa. Electrification rates were recorded by the Sustainable Energy for All (SE4All) initiative and made available at the time of writing by the World Bank[6] at https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS.

Supplementary Table 1: Tariff, reliability, and electrification data by country[4–6]

Country	Retail price @ 100 kWh / month (USD / kWh)	Retail price @ 250 kWh / month (USD / kWh)	Number of electrical outages in a typical month	If there were outages, average duration of a typical outage	Outage Time (computed from number of outages per month and average duration)	Average Service Availability Index = 1 - Outage Time	2014 Electrification Rate
Angola	0.04	0.04	4.7	13.5	8.7%	91.3%	33%
Benin	0.3	0.29	28	3.7	14.2%	85.8%	29%
Botswana	0.1	0.09	4.1	2.7	1.5%	98.5%	53%
Burkina Faso	0.31	0.32	9.8	3.3	4.4%	95.6%	18%
Burundi	0.07	0.13	16.6	4.8	10.9%	89.1%	5%
Cameroon	0.1	0.16	7.6	8.7	9.1%	90.9%	62%
Cape Verde	0.55	0.54	3.2	9.2	4.0%	96.0%	96%
Central African Republic			29	8.1	32.2%	67.8%	3%
Chad	0.18	0.21	19.6	8.8	23.6%	76.4%	4%
Comoros	0.36	0.36					69%
Congo DRC			12.3	5.6	9.4%	90.6%	18%
Congo							42%
Côte d'Ivoire	0.27	0.2	3.5	5.5	2.6%	97.4%	62%
Djibouti							42%
Equatorial Guinea							66%
Eritrea			0.5	2.8	0.2%	99.8%	32%
Ethiopia	0.02	0.03	8.2	5.8	6.5%	93.5%	25%
Gabon	0.25	0.25	4.6	5.4	3.4%	96.6%	89%
Gambia	0.23	0.23	21	6.9	19.8%	80.2%	45%
Ghana	0.12	0.12	8.4	7.8	9.0%	91.0%	72%
Guinea	0.03	0.03	4.5	3.2	2.0%	98.0%	26%
Guinea-Bissau			5.2	17.9	12.8%	87.2%	21%
Kenya	0.23	0.27	6.3	5.6	4.8%	95.2%	20%
Lesotho	0.11	0.11	2.2	6.6	2.0%	98.0%	17%
Liberia	0.51	0.51	1.7	4.7	1.1%	98.9%	10%
Madagascar	0.17	0.17	6.7	1.9	1.7%	98.3%	13%
Malawi	0.08	0.08	6.7	4.3	3.9%	96.1%	12%
Mali	0.27	0.28	4.2	5.1	2.9%	97.1%	26%
Mauritania	0.13	0.12	1.2	3.2	0.5%	99.5%	29%
Mauritius	0.15	0.19	1.2	3.2	0.5%	99.5%	100%
Mozambique	0.11	0.09	1.6	4.3	0.9%	99.1%	40%
Namibia	0.18	0.15	0.6	5.8	0.5%	99.5%	32%

Niger	0.17	0.18	18.5	1.6	4.1%	95.9%	15%
Nigeria	0.14	0.1	32.8	11.6	52.1%	47.9%	45%
Rwanda	0.23	0.23	4	4.3	2.4%	97.6%	27%
Sao Tome and Principe	0.1	0.14					59%
Senegal	0.24	0.27	6	1.8	1.5%	98.5%	61%
Seychelles	0.11	0.11					98%
Sierra Leone	0.19	0.21	13.7	10.2	19.1%	80.9%	14%
Somalia							15%
South Africa	0.1	0.1	0.9	4.5	0.6%	99.4%	86%
South Sudan			1.5	4.7	1.0%	99.0%	1%
Sudan			3.4	2.5	1.2%	98.8%	40%
Swaziland	0.09	0.09	3.7	3.7	1.9%	98.1%	65%
Tanzania	0.12	0.2	8.9	6.3	7.7%	92.3%	30%
Togo	0.24	0.24	5.5	2.1	1.6%	98.4%	27%
Uganda	0.22	0.23	6.3	10.1	8.7%	91.3%	19%
Zambia	0.1	0.08	5.2	2.8	2.0%	98.0%	28%
Zimbabwe	0.07	0.1	4.5	5.2	3.2%	96.8%	52%

Supplementary Note 4

The results by country for the costs of Tier 5 solar systems (Figure 2 of the main text), the reliability premium (Figure 4 of the main text), and the difference between decentralized solar and the grid (Figure 6 of the main text) are presented in Supplementary Table 2, Supplementary Table 3, and Supplementary Table 4, respectively. To be clear, by "results by country" we mean the mean and standard deviation of the values falling with a country's borders sampled at 1-degree latitude by 1-degree longitude. The spatial variation can be seen in the figures in the main text. Note that Cape Verde, Comoros, Sao Tome and Principe, Mauritius, Swaziland, and Togo are omitted because there is no point on the 1-degree latitude by 1-degree longitude sample grid that falls within those countries' borders. Note also that in the case of Nigeria, the high cost of decentralized solar is because the grid reliability is so low (48%), and that designing a decentralized solar system for FDS below 90% results in increasing costs, as shown in Figure 3 of the main text.

Supplementary Table 2: Results by country for Figure 2 from the main text. The table gives the mean and standard deviation of LCOE for all the locations sampled in each country under the current and future economic assumptions

Country	Current decentralized Tier 5 LCOE (mean)	Current decentralized Tier 5 LCOE (std)	Future decentralized Tier 5 LCOE (mean)	Future decentralized Tier 5 LCOE (std)
Angola	0.437	0.021	0.182	0.010
Benin	0.433	0.018	0.181	0.009

Botswana	0.433	0.017	0.181	0.008
Burkina Faso	0.419	0.009	0.174	0.004
Burundi	0.448	0.009	0.189	0.004
Cameroon	0.451	0.036	0.189	0.015
Central African Republic	0.431	0.014	0.180	0.007
Chad	0.406	0.009	0.168	0.004
Congo DRC	0.488	0.009	0.205	0.005
Congo	0.460	0.024	0.193	0.010
Côte d'Ivoire	0.446	0.015	0.187	0.007
Djibouti	0.406	0.007	0.168	0.003
Equatorial Guinea	0.494	0.025	0.209	0.008
Eritrea	0.411	0.011	0.171	0.005
Ethiopia	0.421	0.015	0.175	0.007
Gabon	0.492	0.015	0.207	0.005
Gambia	0.423	0.002	0.176	0.001
Ghana	0.445	0.007	0.187	0.004
Guinea	0.435	0.018	0.181	0.008
Guinea-Bissau	0.441	0.016	0.184	0.007
Kenya	0.420	0.013	0.175	0.006
Lesotho	0.481	0.029	0.201	0.012
Liberia	0.496	0.040	0.207	0.013
Madagascar	0.441	0.025	0.184	0.012
Malawi	0.440	0.015	0.184	0.007
Mali	0.426	0.010	0.178	0.005
Mauritania	0.434	0.011	0.182	0.005
Mozambique	0.453	0.023	0.190	0.010
Namibia	0.428	0.018	0.179	0.008
Niger	0.408	0.010	0.170	0.005
Nigeria	0.453	0.050	0.189	0.020
Rwanda	0.452	0.000	0.191	0.000
Senegal	0.420	0.012	0.175	0.006
Seychelles	0.436	0.005	0.183	0.002
Sierra Leone	0.499	0.023	0.209	0.008
Somalia	0.402	0.012	0.166	0.006
South Africa	0.487	0.036	0.205	0.016
South Sudan	0.440	0.015	0.184	0.007
Sudan	0.409	0.010	0.170	0.005
Tanzania	0.433	0.025	0.181	0.011
Uganda	0.422	0.008	0.176	0.004
Zambia	0.426	0.005	0.177	0.002
Zimbabwe	0.441	0.021	0.184	0.010

Supplementary Table 3: Results by country for Figure 4 from the main text. The table gives the mean and standard deviation of the reliability premium for all the locations sampled in each country under the current and future economic assumptions

Country	Current reliability premium (mean)	Current reliability premium (std)	Future reliability premium (mean)	Future reliability premium (std)
Angola	-0.094	0.013	-0.030	0.004
Benin	-0.104	0.014	-0.033	0.006
Botswana	-0.121	0.030	-0.039	0.010
Burkina Faso	-0.093	0.009	-0.028	0.003
Burundi	-0.102	0.012	-0.033	0.004
Cameroon	-0.100	0.023	-0.031	0.008
Central African Republic	-0.090	0.011	-0.027	0.004
Chad	-0.064	0.021	-0.023	0.008
Congo DRC	-0.111	0.019	-0.033	0.005
Congo	-0.102	0.014	-0.032	0.004
Côte d'Ivoire	-0.107	0.024	-0.034	0.009
Djibouti	-0.107	0.029	-0.041	0.010
Equatorial Guinea	-0.124	0.024	-0.037	0.007
Eritrea	-0.102	0.034	-0.037	0.012
Ethiopia	-0.079	0.019	-0.029	0.006
Gabon	-0.133	0.019	-0.039	0.006
Gambia	-0.171	0.022	-0.051	0.006
Ghana	-0.153	0.083	-0.047	0.024
Guinea	-0.116	0.024	-0.037	0.009
Guinea-Bissau	-0.178	0.013	-0.056	0.005
Kenya	-0.090	0.037	-0.030	0.011
Lesotho	-0.192	0.028	-0.061	0.010
Liberia	-0.154	0.052	-0.048	0.016
Madagascar	-0.188	0.059	-0.059	0.017
Malawi	-0.109	0.028	-0.036	0.008
Mali	-0.154	0.048	-0.051	0.014
Mauritania	-0.198	0.027	-0.061	0.007
Mozambique	-0.163	0.047	-0.052	0.015
Namibia	-0.103	0.024	-0.033	0.007
Niger	-0.084	0.027	-0.031	0.011

Nigeria	-0.120	0.051	-0.039	0.020
Rwanda	-0.087	0.000	-0.027	0.000
Senegal	-0.167	0.029	-0.050	0.009
Seychelles	-0.173	0.023	-0.055	0.008
Sierra Leone	-0.155	0.040	-0.048	0.011
Somalia	-0.122	0.047	-0.041	0.014
South Africa	-0.163	0.031	-0.052	0.010
South Sudan	-0.092	0.009	-0.028	0.003
Sudan	-0.063	0.023	-0.022	0.007
Tanzania	-0.115	0.048	-0.038	0.015
Uganda	-0.085	0.011	-0.027	0.003
Zambia	-0.115	0.027	-0.039	0.009
Zimbabwe	-0.161	0.029	-0.053	0.007

Supplementary Table 4: Results by country for Figure 6 from the main text. The table gives the mean and standard deviation of the difference between the LCOE of solar and the grid tariff for all the locations sampled in each country under the current and future economic assumptions

Country	Current LCOE difference: solar - grid tariff (mean)	Current LCOE difference: solar - grid tariff (std)	Future LCOE difference solar - grid tariff (mean)	Future LCOE difference solar - grid tariff (std)
Angola				
Benin	0.240	0.108	-0.016	0.105
Botswana	0.382	0.050	0.102	0.022
Burkina Faso				
Burundi				
Cameroon				
Central African Republic				
Chad				
Congo DRC				
Congo				
Côte d'Ivoire				
Djibouti				
Equatorial Guinea				
Eritrea				
Ethiopia				
Gabon	0.268	0.019	-0.036	0.005
Gambia	0.185	0.005	-0.077	0.010

Ghana	0.306	0.044	0.051	0.044
Guinea				
Guinea-Bissau				
Kenya				
Lesotho	0.507	0.086	0.143	0.029
Liberia	0.130	0.087	-0.222	0.104
Madagascar	0.308	0.034	0.031	0.015
Malawi	0.365	0.068	0.093	0.052
Mali	0.207	0.104	-0.058	0.077
Mauritania	0.432	0.057	0.102	0.040
Mozambique	0.426	0.078	0.118	0.042
Namibia	0.337	0.042	0.056	0.023
Niger	0.246	0.044	0.005	0.041
Nigeria	0.394	0.023	0.132	0.009
Rwanda	0.249	0.000	-0.012	0.000
Senegal	0.175	0.015	-0.084	0.007
Seychelles				
Sierra Leone	0.255	0.005	-0.015	0.003
Somalia				
South Africa	0.525	0.065	0.152	0.023
South Sudan				
Sudan				
Tanzania	0.230	0.026	-0.020	0.020
Uganda				
Zambia	0.358	0.010	0.101	0.009
Zimbabwe	0.354	0.028	0.090	0.013

Supplementary References

1. Levin, T. & Thomas, V. M. Can developing countries leapfrog the centralized electrification paradigm? *Energy Sustain. Dev.* **31,** 97–107 (2016).

2. Szabó, S., Bódis, K., Huld, T. & Moner-Girona, M. Sustainable energy planning: Leapfrogging the energy poverty gap in Africa. *Renewable and Sustainable Energy Reviews* **28,** 500–509 (2013).

3. Bhatia, M. & Angelou, N. *Beyond Connections Energy Access Redefined, Technical Report 008/15*. *Technical Report 008* **8,** (The World Bank, 2015).

4. Trimble, C., Kojima, M., Perez-Arroyo, I. & Mohammadzadeh, F. *Financial Viability of Electricity Sectors in sub-Saharan Africa. Quasi-fiscal Deficits and Hidden Costs*. *Policy Research Working Paper 7788. World Bank* (The World Bank, 2016).

5. The World Bank. Enterprise Surveys. (2017). Available at:

http://www.enterprisesurveys.org/data/exploretopics/infrastructure#sub-saharan-africa.

6. The World Bank. Access to electricity (% of population). (2014). Available at: https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS. (Accessed: 8th November 2017)