Satellite Observations Reveal Inequalities in the Progress and Effectiveness of Recent Electrification in Sub-Saharan Africa

Giacomo Falchetta, Shonali Pachauri, Edward Byers, Olha Danylo, & Simon C. Parkinson

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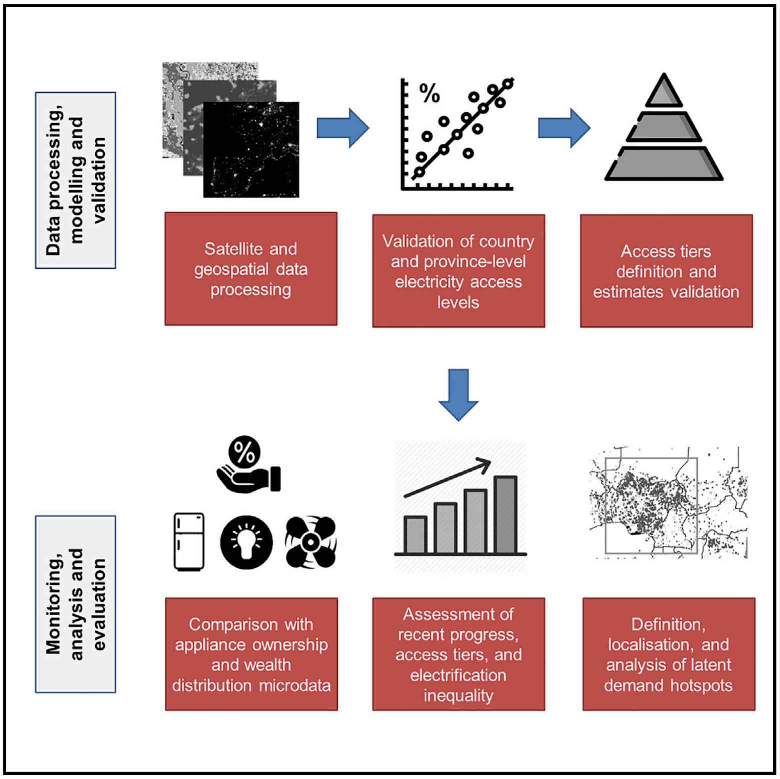
Graphical Abstract



Highlights

- 115+ million in sub-Saharan Africa gained access to electricity in 2014–2019
- Most electrified households benefit from low-tier electricity access
- The pace of electrification must more than triple to fulfill SDG 7.1.1 by 2030
- Inequalities may persist if efforts solely aim at increasing new connections

Authors

Giacomo Falchetta, Shonali Pachauri, Edward Byers, Olha Danylo, Simon C. Parkinson

Correspondence

giacomo.falchetta@feem.it

In Brief

Energy poverty is widely diffused and persistent in sub-Saharan Africa. Even in areas that formally have access to electricity, power consumption and supply reliability are largely inadequate. We derive multi-dimensional estimates of electricity access over space and time by processing high-resolution population distribution maps, satellite-measured nighttime light, and settlement locations for sub-Saharan Africa. Our results reveal wide inequalities in the pace and quality of electrification, which cannot be observed in existing statistics.

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Satellite Observations Reveal Inequalities in the Progress and Effectiveness of Recent Electrification in Sub-Saharan Africa

Giacomo Falchetta,[1,2,3,5,*] Shonali Pachauri,[3] Edward Byers,[3] Olha Danylo,[3] and Simon C. Parkinson[3,4]
[1]Fondazione Eni Enrico Mattei, Corso Magenta 63, 20123 Milan, Italy
[2]Department of International Economics, Institutions and Development, Cattolica University, Largo Gemelli 1, 20123 Milan, Italy
[3]International Institute for Applied Systems Analysis, Schossplatz 1, Laxenburg, Austria
[4]Institute for Integrated Energy Systems, University of Victoria, PO Box 3055 STN CSC, Victoria, BC, Canada
[5]Lead Contact
*Correspondence: giacomo.falchetta@feem.it
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SCIENCE FOR SOCIETY Energy poverty is widely diffused and persistent in sub-Saharan Africa. Even in areas that formally have electricity access, power consumption and supply reliability are largely inadequate. Yet, most institutional statistics fail to capture these different dimensions and rely on rapidly outdated and unwieldy household surveys. In this study, we process high-resolution population distribution maps (including demographic and migration trends), satellite-measured nighttime light, and settlement information for sub-Saharan Africa. This allows us to derive multi-dimensional estimates of electricity access over space and time and compare them with a set of published records. Our results reveal wide inequalities in the pace and quality of electrification, which cannot be observed in existing statistics. We show that the pace of electrification must more than triple to fulfill SDG 7.1.1 and discuss why electrification policy could fall short if aimed solely at boosting electricity connections.

SUMMARY

Ending energy poverty is a necessary condition for achieving the Sustainable Development Goals (SDGs). Boosting electricity access levels is, however, insufficient if consumption and reliability indicators stagnate. Previous research has shown that satellite-derived data can complement field surveys in tracking energy poverty but with little consideration for the multi-dimensionality of energy access and the role of demographic dynamics. Here, we process 6 years of high-resolution population, nighttime light, and settlement data for sub-Saharan Africa to derive multi-dimensional estimates of electricity access. Our results, validated against a range of sources, confirm a recent surge in electrification such that >115 million people gained access over the 2014–2019 period. Yet, they reveal wide inequalities in the quality of electrification, which cannot be observed in the existing statistics. The pace of electrification must more than triple to fulfill SDG 7.1.1 by 2030. Efforts could fall short if aimed solely at boosting numbers of national electricity connections.

INTRODUCTION

In 2019, the International Energy Agency (IEA) reported that the global population without access to electricity had dipped below 1 billion for the first time.[1] Yet, the numbers released in the *Tracking SDG7: Energy Progress Report 2019*[2] highlight that this progress has been uneven both across and within different macro-regions of the world.[3,4] The bulk of the improvements have been observed in Central and Southern Asia and a few areas of Africa. In fact, nearly two-thirds of those still without access to electricity—about 570 million people—are located in sub-Saharan Africa. The continent is home to 30 countries with electrification levels below 50%.[2] At the same time, while recent evidence shows that falling costs might soon make electricity an attractive alternative for satisfying cooking needs,[5,6] most cooking activity in the region still relies on solid-biomass[2] (with the notable exception of South Africa, where electricity has gained a prominent role[7]), contrary to what is targeted by Sustainable Development Goal 7 (SDG 7) indicator 7.1.2.

While these statistics provide a clear picture of global trends, fundamental uncertainties remain. First, electricity access is still measured in a mostly binary fashion, as the share of a country's population that has access to an electric energy supply source. Binary indicators are inherently limited if highly aggregate and by mono-dimensionality and disregard crucial questions such as reliability of supply and the effective use beyond nominal access provision.[8,9] Such dissatisfaction has spurred the development of new measurement frameworks, a leading one being the World Bank Multi-Tier Framework[10] (MTF) (Figure S1), but few data based on these approaches have emerged (survey results for Zambia, Ethiopia, and Rwanda have been published online[11] as of early 2020). Moreover, according to SDG 7's energy abundance and mobility requirements,[12] only populations with access through the national grid or mini-grid solutions are compliant with sufficient energy access standards, while standalone decentralized solutions,[13] such as solar kits, can be inadequate (although the surge in their installation[14,15] and their role as a first step up the energy ladder[16,17] must be acknowledged). Second, the most common electricity access statistics are expressed at the national scale and thus fail to reflect sub-national heterogeneity. More spatially detailed information is, however, essential for clearly determining the electrification status of a country and tracking its progress toward the SDGs. Third, electricity access measurement relies predominantly on expensive and unwieldy household surveys that are labor intensive and rapidly outdated. Finally, it has been shown[18] that in African countries official statistics, including statements and numbers on progress toward universal and reliable energy supply,[19] can be affected by statistical growth. This is defined[20] as growth of development indicators occurring by assumption in the absence of reliable information or with the deliberate objective of attracting more foreign investment. In fact information provided by Governments and Ministries is the same as the material that is readily accessible from international databases.

Satellite data have been employed in earlier studies[21–24] to quantify electricity access levels by assessing the presence of radiance with a wavelength compatible with that of electric light during nighttime hours.[25,26] Previous seminal applications have shown that combining nighttime lights and human settlement datasets can proxy electricity access levels and track the rollout of electrification even at a local scale.[27,28] These data have also been used to model changes in electricity consumption within provinces (in countries where disaggregated data are available for validation purposes),[29,30] detect power supply disruptions[31] and outages,[32,33] map the power transmission and distribution infrastructure,[34] and measure economic development and inequality sub-nationally.[35] Yet, the main limitations of the literature exploiting nighttime lights to keep track of electricity access in developing countries include the fact that light has been considered mostly in a binary fashion, without exploring the effective level of radiance detected and exploiting it to derive and validate proxy measures of electricity access quality for electrified households in data-scarce regions. Moreover, little is known of how well satellite nighttime lights imagery can be used to assess access through different technological solutions—which is crucial due to the surge of mini-grids[36]—and predict inequalities in electricity access progress and effectiveness (i.e., the quality of access provided) at sub-national scales. In fact, there seems to be no previous attempt of province-level assessment and validation. Hitherto, the focus has been mainly on static snapshots that did not explore the interdependencies of changing demography, growing urbanization, and nighttime light distribution for electricity access assessment. The relationship between within-country electrification trends, the distribution of wealth within countries, and statistics about appliance ownership represent further unexplored questions. Finally, published studies exploiting nighttime lights to assess electrification have not provided means and code to update results or transpose the analysis to other scales. Today, new and improved satellite data products that are being frequently updated allow for considerably greater precision through improved sensitivity and spatial resolution.[37–39] Cloud-computing platforms help leverage these data and make analysis accessible to those without high-performance computational facilities.[40]

Here, we capitalize on these developments and assess the potential of satellite data to support institutions devoted to tracking electricity access (i.e., progress toward SDG 7's target 7.1.1) by complementing and validating a variety of household derived information on electricity access, consumption, and appliance ownership at a community and country level with a low-cost geospatial indicator that can be updated easily and in near real-time. To achieve this, we analyze remotely sensed nighttime light radiance data for sub-Saharan Africa combined with georeferenced demographic distribution and settlement type information and other spatially explicit layers for the 2014–2019 period. We estimate sub-national indicators of electricity access inequality that provide insight into the progress toward SDG 7 targets at a provincial scale and across rural and urban regions. Crucially, our analysis goes beyond conventional binary measurement by linking electricity use to luminosity to define tiers of access based on the World Bank MTF.[10] This enables estimating energy poverty even where electricity infrastructure is available. We confirm the recent increase in the pace of electrification in sub-Saharan Africa, where >115 million people gained access over the 2014–2019 period. However, we reveal wide inequalities in the quality of electrification, with a vast distribution across access tiers that cannot be observed in the existing statistics. These results suggest the need to critically evaluate the success of electrification programs beyond their role in boosting the national electricity access statistics.

RESULTS

Estimates of Recent Electrification Trends

A country-level aggregation of our bottom-up high-resolution estimates reveals that over the 6-year 2014–2019 period, electricity access in sub-Saharan Africa grew robustly such that more than 115 million people became newly electrified. This has led to about a 5-percentage-point (p.p.) increase in the regional electricity access level (growing from 42% to 47%) despite a growing population (by 14%, i.e., +144 million). The remotely sensed estimates are not dissimilar from the aggregate numbers found in the SE4ALL Global Tracking Framework database, which reports a 6.3 p.p. decline in the share of the population without access between 2014 and 2017, such that the regional electricity access level grew from 38.3% to 44.6%. This represents a

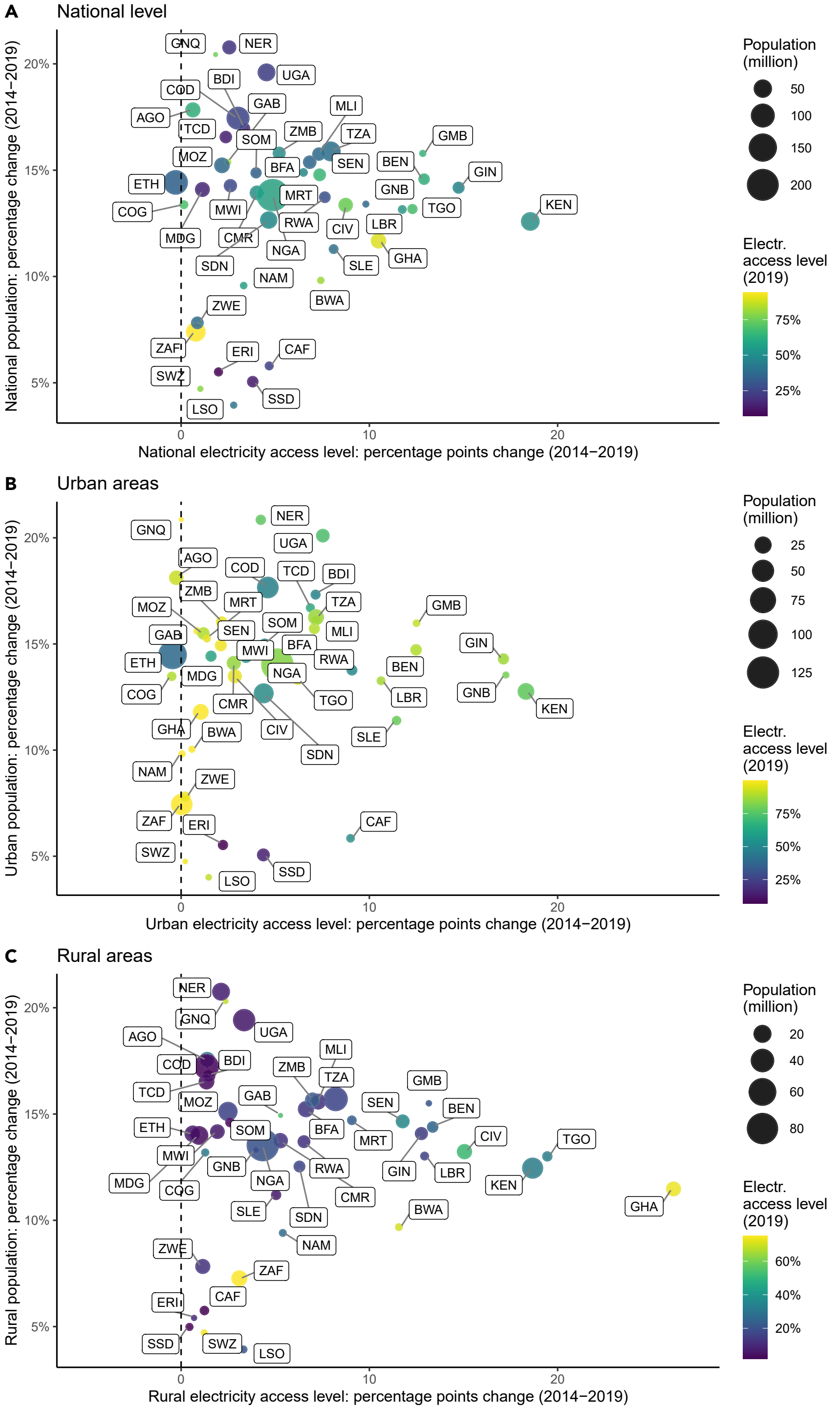

Figure 1. Electrification Level Change (in Percentage Points) and Population Change (in Relative Terms) in Sub-Saharan Africa in 2014–2019

Results are grouped at the national (A), urban (B), and rural (C) scales. Colors describe the electrification level in 2019 (in percentage points), and the size of circles is proportional to the population size in 2019 (in millions of people). The classification method for urban and rural areas, achieved at a 250-m resolution, is discussed in the Experimental Procedures and is consistent with the urbanization level reported by the World Bank. ISO code labels identify countries as clarified in the codebook in Table S2.

significant acceleration with respect to the electricity access growth rates observed in the previous decades (e.g., according to the SE4ALL Global Tracking Framework database, in the 10-year 2000–2009 period, the regional electricity access level grew by only 8 p.p.). Potential reasons behind this recent surge may include the momentum created by the introduction of the SE4ALL initiatives and the SDGs, which are discussed in the paper.

Figure 1 includes three panels (for national, urban, and rural scales), each plotting the 2014–2019 progress (in percentage points) of the estimated electricity access levels on the x axis and the relative change (in percentages) in the population over the same time period. The graphs thus depict the tradeoff between demographic change (encapsulating both population growth and urban-rural migration; see the Experimental Procedures) and electrification rollout. Each country is represented by a bubble whose size is proportional to the total population and whose color describes the estimated level of electricity access level reached at the end of 2019.

When looking at the results at the national level, a picture of a heterogeneous and yet general improvement throughout the continent emerges. The only country where we estimate a quasi-negative electricity access growth is Ethiopia. Ethiopia, Nigeria, and the Democratic Republic of the Congo are in fact the three countries with the largest absolute number of people without access to electricity, accounting together for 231 million people, i.e., nearly 40% of those without access on the continent. In general, we find that countries with the largest rural electrification deficit are characterized by a rapid rural population growth (e.g., Niger, Uganda, the Democratic Republic of the Congo, Chad, or Burundi), which perpetuates a vicious circle that is then reflected in limited national access and progress levels. Conversely, a set of countries showing rapid electrification growth at the national scale also show the highest increases in electrification levels in rural areas, for instance Kenya, Togo, Benin, and Guinea. While rural electrification remains the first concern (with notable exceptions in South Africa, Botswana, Eswatini, and an increasingly improved situation in Kenya, Côte d'Ivoire, Senegal, and Togo), in some countries urban areas

Table 1. Comparison of Estimates with Multiple Electrification Statistics Databases

Data Source(s)	Time Interval of Access Data Points	Correlation (ρ) with Most Recent Measurement	Correlation (ρ) of Progress
Tracking SDG7: The Energy Progress Report 2019[2] and the *Atlas of the Sustainable Development Goals*[15]	1990–2017	0.86	0.28 (2014–2017)
Africa Energy Outlook 2019[13]	2000–2017	0.81	0.08 (2010–2017)
DHS STATcompiler[41] household surveys (various years, province level)	2014–2017	0.82	–

are a growing source of concern. For instance, we estimate the urban electricity access level of Ethiopia to have remained nearly constant over the last 6 years as a result of a near 15% growth of the population living in cities—and therefore an urban electricity access deficit of 56 million people. Other countries with urban electricity access issues include Eritrea, South Sudan, the Democratic Republic of the Congo, Burundi, Sudan, Rwanda, the Central African Republic, and Madagascar. In these cases, migration to cities and population growth dynamics in peri-urban and urban areas are likely to contribute to these trends, nearly outpacing electrification.

To evaluate the quality of our estimates, we compared them with the most recent available electricity access statistics from multiple sources (see Figure S2 for scatterplot comparisons). In particular, as summarized in Table 1, these sources include *Tracking SDG7*: *The Energy Progress Report 2019*,[2] the *Atlas of the Sustainable Development Goals*,[2,15] the *Africa Energy Outlook 2019* (which reports slightly different country-level figures),[13] and the Demographic Health Survey (DHS) STATcompiler household surveys,[41] through which a multiannual province-level electricity access dataset including all countries with information available between 2014 and 2019 was compiled and then parsed to our province-level estimates for the corresponding survey year. Table 1 shows the results of the correlation analysis for the electricity access levels. The results reveal that our estimates are highly consistent with the most recent available yearly estimates (ρ between 0.81 and 0.86) at both the country level and when assessing provinces within countries. Yet, when evaluating the consistency with the percentage-point chang, i.e., the improvement in access in recent years, the correlation sinks (ρ between 0.08 and 0.28). That is to say, our estimates are consistently in agreement with the latest measurements but not in agreement for all countries about the improvements that have occurred in recent years.

The potential reasons behind the measured discrepancy in the progress juxtaposed with the high consistency in the current situation estimates are multiple. First, the nighttime light radiance is a metric of electricity access that is only able to detect electricity use that (1) is overnight, when the satellite overpass takes place; (2) is resulting in some form of visible light radiance (which might include indoor and/or public lighting); or (3) has a sufficient intensity to be detected by the satellite sensor, i.e., is above some very low threshold of final use. The implications of this point are discussed in greater detail in the section Uncertainty and Limitations. From a conceptual point of view, a missed detection of populations with access to electricity (which results in an underestimation of recent progress compared with the official statistics) is likely to be the result of a very low final use, i.e., of a hitherto low effectiveness of electrification. For instance, in those countries where the strongest most recent electrification is reported by official statistics, we observe the greatest discrepancies, namely Kenya, Ethiopia, and the Republic of the Congo, while in many others near-perfect validation is achieved.

Second, and relatedly to the previous point, in related ongoing research we find that populations served by mini-grids are well captured by satellite imagery but that satellite-based information might not be able to capture standalone decentralized solutions such as household-scale diesel gensets and solar home systems, which have been a strong driver of the recent surge in electricity access level throughout sub-Saharan Africa.[42] Yet, this limitation is linked to the fact that the concept of access to electricity does not have a unique widely agreed definition.[43] A heated debate over the quantification of the minimum levels of electric energy use deemed necessary to define access is ongoing.[8–10] One of the crucial arguments is that energy access and energy poverty are not mutually exclusive. At the same time, energy access is not a static concept but instead should be considered a dynamic process following a "ladder,"[12,44–46] where different technologies and solutions gradually replace the previous ones, providing greater power and supporting more appliances and uses. In this paper, we make an explicit choice in excluding standalone solutions from the definition of energy access because of the very limited amount of energy (and in turn of appliances) they are able to supply (although we acknowledge their role as a first step up the energy ladder,[17,46] e.g., by saving costs and health burdens associated with kerosene use and allowing for more education through nighttime study and access to telecommunications).

Third, it must be highlighted that inconsistencies and discontinuities across different years are evident in the official statistics. These issues are compatible with the notion of statistical growth, i.e., growth occurring by assumption in the absence of reliable information (e.g., with statistical extrapolations performed by governments or from development agencies publishing the numbers) or with the deliberate objective of attracting more foreign investment. Refer to Figure S3, which statistically confirms the existence of a linear time trend in official electrification statistics while ruling out that of higher-order polynomial relationships. Together, these considerations suggest that caveats are required in the comparison with official statistics (which depending on each country's statistical office can include different types of access solutions, including solar lamps or standalone diesel generators) with interannual satellite-based estimates, which are mostly able to capture access through the national grid and mini-grids. However, this also implies that the poor results of the recent progress estimates with the official statistics have specific underlying reasons that might not be related to an

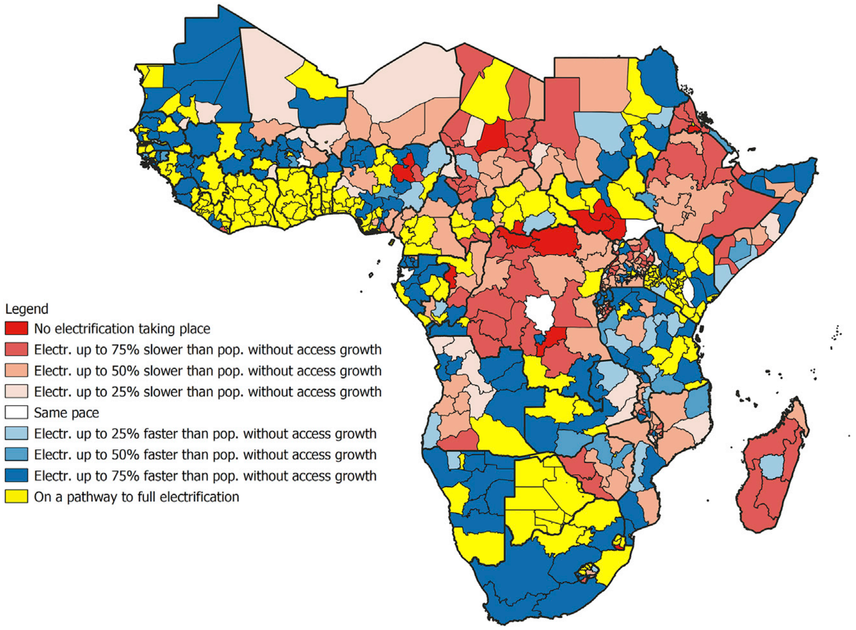

Figure 2. Provincial Changes in the Number of People Gaining Access and the Number of New People with Access to Electricity between 2014 and 2019

The color scheme categorizes the data across two dimensions: the growth in the population without access and the growth in the electrified population. Two additional categories identify provinces where the population with and without access have declined.

ineffective methodology but merely to the assumptions it encapsulates and what is actually measured.

Inequalities in Sub-national Electrification Progress

To understand the heterogeneity at the province level in the recent progress with electricity access, it is crucial to disentangle the interplay between the electrification rollout and the growth in the population without access induced by demography and migration. In Figure 2 we map the ratio between the change in the absolute number of people with and without access in each province between 2014 and 2019. The metric suggests the geographic position and density of areas where electrification rollout has surpassed (or been slower than) the growth in the population without access to electricity. It also indicates provinces where we estimate that no electrification is taking place (no or negative growth in the population with access to electricity) and those areas where—conversely—a negative or null growth in the population without access to electricity was experienced in the period examined. The latter are classified as on a pathway to full electrification. Yet, it must be remarked that they might also identify areas where little electrification has been implemented and yet the electricity access rate has increased due to a decline in the population without access. These situations include provinces experiencing emigration toward other provinces or countries. The analysis reveals significant electrification progress over large parts of southern Africa (in South Africa, Namibia, and Botswana, and several regions of Angola and Zambia), throughout Kenya and in most provinces of Tanzania and Sudan, and in most West African provinces surrounding the Gulf of Guinea (in Ghana, southern Nigeria, Côte d'Ivoire, Benin, Togo, and Cameroon). At the same time, the map reveals much slower electrification progress in Ethiopia, in most provinces of Central Africa (and chiefly in the Democratic Republic of the Congo), over large parts of Uganda and Burundi, in Chad, and in multiple areas of the Sahel.

The analysis also indicates that in provinces where income is more unevenly distributed, today's electrification access levels tend to be lower (Table S1, model 1). In particular, we find that each percentage-point increase in the province-level Gini index of wealth inequality estimated using DHS survey data is associated with an average 1.46-p.p. lower satellite-measured local electricity access level (with $p < 0.01$). This suggests that these provinces might have historically been less targeted by electrification expansion programs[47] or even that where the grid exists, households in such provinces have had insufficient income to afford connection[48] and running costs, so only a few have benefited from electricity use. On the other hand, there is a likelihood that those with electricity may have become wealthier from having access. In contrast to the results for electricity access per se, our province-scale estimates of electrification progress over the last 6 years are found to be positively correlated (Table S1, model 2) with the Gini index of wealth inequality ($p < 0.01$). While the magnitude of this association is still very small, close to 0, this result could indicate that in recent years a trend change has occurred, and electrification efforts are now concentrating on areas where income today is more unevenly distributed.

National-scale urban and rural electricity access Lorenz curves for 2014 and 2019, and the forward difference (Figure 3) provide further insight into the inequalities in electrification progress. The results show, for example, that in 2014 electricity access inequality was similar in urban and rural areas of Rwanda. Since then, robust progress has been made in the country, particularly among low-electrified provinces and rural areas, while urban electrification levels have stagnated. Conversely, in rural Kenya progress has been more concentrated in provinces with electrification levels above the second quartile, with a focus on universalizing access in already connected areas and stagnation in several provinces with low access levels. Overall, the select countries represented show heterogeneity in inequality, with unequal distributions in provincial-level electricity access in Ethiopia and the Democratic Republic of the Congo. Calculation of a population-weighted Gini index of electricity access inequality G (see the Experimental Procedures) reveals that while urban inequality in electricity access has been declining throughout countries of sub-Saharan Africa, in rural areas inequality has increased over the 6-year period in some countries, e.g., Namibia, Sudan, Niger, and the Democratic Republic of the Congo. The countries with the highest provincial

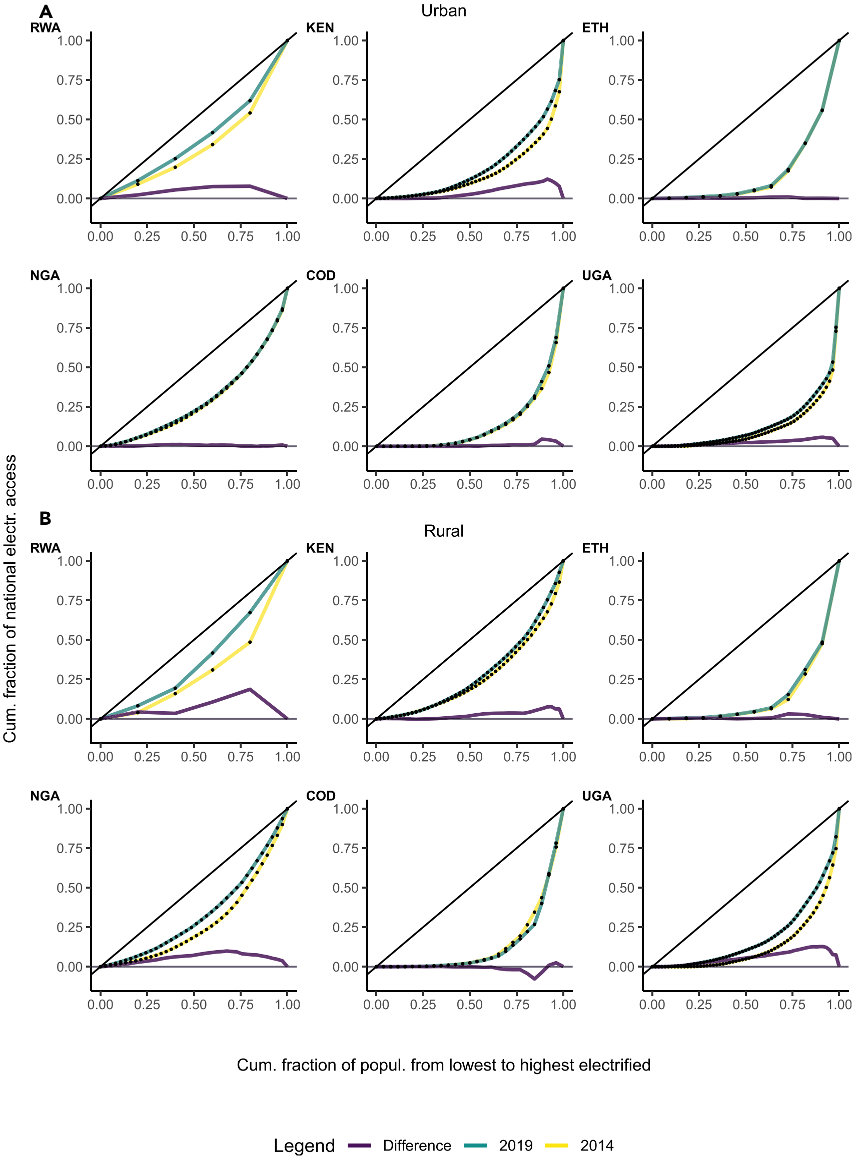

Figure 3. Electricity Access Lorenz Curves for 2014 and 2019, and the Forward Difference, for Selected Countries

Results are grouped for urban (A) and rural (B) areas. The closer the 2014 and 2019 Lorenz curves to the 1:1 line, the lower the access inequality. Larger spaces between the curves represent greater change between 2014 and 2019, which is also visualized by the red difference curve.

inequality in urban electricity access growth are the Central African Republic, Liberia, Chad, and Uganda ($0.72 \leq G \leq 0.81$). Low urban inequality is found in Rwanda, Sierra Leone, and Benin ($0.24 \leq G \leq 0.35$). On the other hand, in rural areas inequality is prevalent in the Democratic Republic of the Congo, Chad, Ethiopia, and the Republic of the Congo ($0.65 \leq G \leq 0.73$). Lowest rural inequality is estimated in Togo, Ghana, Zambia, and Mozambique ($0.07 \leq G \leq 0.21$). However, crucially, low inequality may encompass situations whereby everyone lacks access.

Assessing the Uneven Quality of Electrification

A binary access indicator does not provide any information on whether populations in an electrified area benefit equally from the same level of access (F. Riva et al., 2018, 36th International Conference of the System Dynamics Society). Recent empirical evidence[49] has shown that a significant issue related to electricity access expansion is that low consumption levels may persist among those that are connected due to limited power availability and affordability and reliability issues,[50] thus causing a first-order problem for the sustainability of utilities and the development prospects of communities. To distinguish between different levels of electricity use among those who have electricity access, we create four per-capita light intensity categories (see the Experimental Procedures and Figure S4) to proxy residential electricity use and validate them on recent household survey data building on the World Bank MTF for measuring electricity access quality. In the validation exercise, our tiers 0 (no access) and 1 correspond to MTF tiers 0 and 1 (i.e., access via pico-scale access solutions) and are grouped together. This is because very low levels of available power, final electricity use, and reliability are here regarded as a lack of access. Conversely, our tier 4 is coupled with MTF tiers 4 and 5 together because at higher levels of electricity use, nighttime light becomes a marginally worse predictor of final consumption (see Falchetta and Noussan[51] for empirical evidence for this statement). Refer to the Experimental Procedures for a detailed account of the underlying reasoning and data-processing steps.

Table 2 illustrates the results of the validation procedure, which is carried out for the three countries for which multi-tier data are available thanks to field data-collection efforts by the Energy Sector Management Assistance Program (ESMAP). These are Ethiopia, Zambia, and Rwanda. As seen more in detail in the by-tier, by-settlement type, and by-country validation plots in Figure S5, the method is effective at reproducing the distribution of people among tiers of electricity access reported by the ESMAP. In particular, the validation is very precise for the total population and the rural areas in every country, while the main source of mismatch is found in urban areas of Ethiopia, where we underestimate the proportion of people at higher tiers.

Having provided a proof of concept of the general effectiveness of the approach, we generalize the analysis of the distribution of populations among electricity access tiers across all countries in sub-Saharan Africa. Figure 4 summarizes the results of the assessment for national, urban, and rural populations.

Table 2. Comparison of Access Tier Estimates with Multiple Household Surveys

Survey	Surveying Period(s)	Correlation (ρ) between the Distributions for Survey Data and the NTL-Based Estimate
ESMAP MTF Survey Zambia	2018–2019	0.92
ESMAP MTF Survey Ethiopia	2017–2018	0.65
ESMAP MTF Survey Rwanda	2017–2018	0.87

NTL, nighttime lights.

When examining distributions at a national scale, the assessment reveals that the countries where people with access to electricity are classified among the highest tiers of access include Angola, Botswana, Côte d'Ivoire, the Republic of the Congo, Gabon, Ghana, Equatorial Guinea, and South Africa. Lower-tier access is prominent among Benin, Ethiopia, Guinea, Guinea-Bissau, Kenya, Liberia, Nigeria, Eswatini, and Togo. In general, countries with large shares of the population at tier 0 of electricity access also exhibit more inequality in the distribution across tiers, with many without access and few concentrated in high-consumption tiers (presumably in the main cities, where the bulk of electrified people are located): these include Burundi, the Central African Republic, Chad, the Democratic Republic of the Congo, Malawi, Niger, and Uganda.

Restricting the analysis to urban areas shows that in a large number of countries, most grid-connected consumers benefit from relatively high levels of electricity access. Electricity supply reliability is, however, an issue in many cities[52] irrespectively of the average yearly final consumption. Exceptions include, for instance, Burundi, the Central African Republic, Eritrea, Ethiopia, Guinea-Bissau, Liberia, Madagascar, Malawi, Niger, Rwanda, Sierra Leone, Somalia, and South Sudan. In these countries, we estimate that less than 25% of electricity-consuming urban households benefit from access at tier 4 or above. Conversely, it is evident how the bulk of the electricity access deficit exists in rural areas, with rural access levels below 25% in most countries except the few wealthier nations. In particular, we estimate rural access levels greater than 50% only for Botswana, Gabon, Ghana, Equatorial Guinea, Swaziland, and South Africa. Interestingly, all these countries are characterized by a strong role of the natural-resource extractive sector.

So what about the link between wealth inequality and electricity access? We calculated the province-level association between the estimated average tier of electricity access (obtained by a pixel-level weighted multiplication of population with access to electricity and the local estimated prevalent access tier) and the local Gini coefficient of wealth inequality obtained from the DHS survey data. We control for country fixed effects. The strongly negative result (Table S1, model 3) shows that an average increase of about 0.21 points in the Gini coefficients is associated with a 1-tier shift in the locally prevalent access tier. This result—albeit not causal—is consistent with assessments in the literature linking electricity use with poverty and inequality.[49–54] The theoretical reasons underlying this empirical finding include the political and economic factors affecting the propensity of policymakers to concentrate their electrification investment toward certain regions,[55–57] the uneven load-shedding policies that have been shown to disproportionately hurt the poor,[58] and the fact that provinces where there is a high income inequality are more likely to be less electrified—as empirically observed in this paper—and thus the existing distribution grid is likely to be serving only the few rich people, who are also more likely to have electricity through standalone solutions. To provide a further line of validation, using data on appliance ownership, we assess the association between the province-scale estimated average tier of electricity access among people with access to electricity and ownership of different electric appliances derived from DHSsurveys, including radio, mobile phone, television, and refrigerator. Our results, summarized in Table S1 (models 4–7), suggest a strong and positive correlation between access tier and ownership for each of the four appliances. In particular, on average, advancing by one access tier (as estimated with our methodology) implies a 21-p.p., 13.2-p.p., 10-p.p., and 6.8-p.p. average increase (at $p < 0.01$) in the propensity of a representative household at province level to own a television, a refrigerator, a mobile telephone, and a radio, respectively. These results provide a further layer of validation to our nighttime-light-based approach to assess electricity access multi-dimensionally.

Hotspots of Growing Access and Demand Deficits

To identify potential hotspots of high unelectrified population and unmet demand density, we distinguish two types of areas: (1) regions where the latent or unmet demand is likely to rise, i.e., where use remains very low despite relatively high nominal access levels (see the Experimental Procedures for details); and (2) areas that have exhibited the fastest growth in population without access to electricity (Figure 5A). Overlaying these two separate regions helps us to identify five major hotspots: (1) in West Africa, in proximity to the coastal areas of Côte d'Ivoire, Liberia, Sierra Leone, and Guinea (a macro-area hosting nearly 57 million people without access); (2) in the Gulf of Guinea, over Togo, Benin, and Nigeria (where we estimate 100 million people with no electricity access); (3) in large parts of Ethiopia and the Horn of Africa (an additional 100 million people without access); (4) across densely populated Burundi, Rwanda, Uganda, and southern Malawi (around 130 million without access); and (5) in the eastern regions of Madagascar (nearly 15 million without access). Other regions with a high density of people without access include the Democratic Republic of the Congo and Angola. In addition, regions in West Africa, northeast of Lake Victoria, between Uganda and Kenya, and in southern Africa include areas with high potential for latent demand growth. These include regions where the number of people without access to electricity has not increased much but where there are several electrified areas with low current use.

Figure 5B shows the empirical cumulative distribution curves of the population living in the identified hotspots against the travel time to the nearest city with 50,000+ inhabitants. The

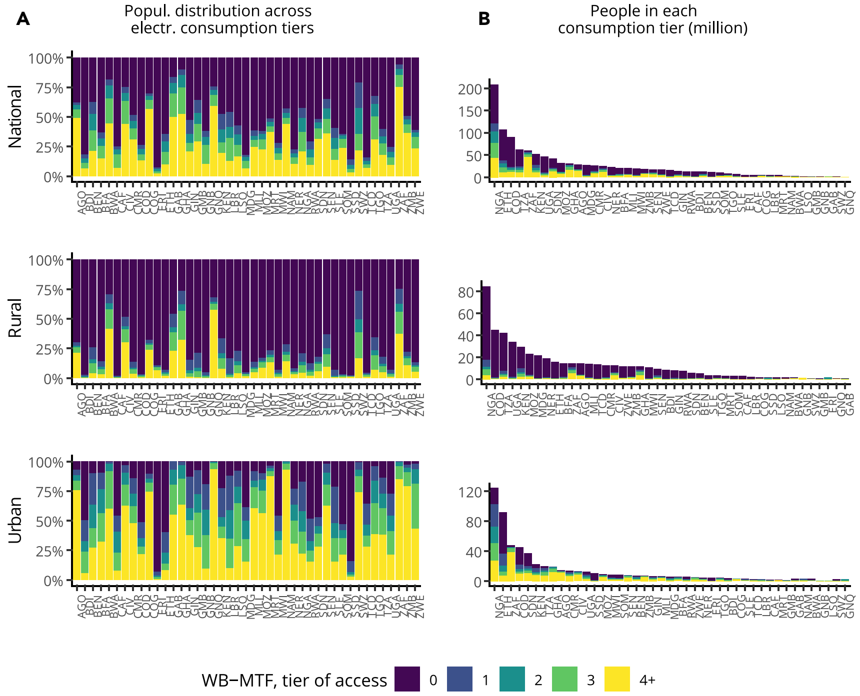

Figure 4. Bar Plots Representing the Estimated Residential Electricity Access Tiers in National, Urban, and Rural Areas

(A) Frequency of population in each tier relative to the national, urban, and rural populations.

(B) Absolute number of people in each tier for national, urban, and rural populations of each country.

analysis reveals that more than half of the growth in populations without access between 2014 and 2019 has taken place in settlements that are less than 2 h away from the nearest city, while only about 20% of the total are in regions ≥4 h away. The picture is even more striking when looking at hotspots of latent demand: we find that over three-quarters of these populations are within a 1-h journey to a city, meaning that latent demand among households formally classified as having access to electricity is predominantly a peri-urban issue. Finally, we also observe that the areas that we identify as hotspots of lack of electricity access and latent demand largely overlap areas exposed to vulnerability to climate hazards.[60] Recent evidence has suggested a surge in the future demand for cooling[61]—and in turn for energy[62]—in an array of climate scenarios. It is clear that a lack of sufficient, reliable, affordable access to electricity would impair the provision of cooling services and thus negatively affect socioeconomic outcomes, chiefly health,[63] and cognitive performance.[64]

Uncertainty and Limitations

An explicit account of the limitations must necessarily supplement studies that are based on remote-sensing and geospatial data analysis and aim to measure information that ideally would be collected in the field. While the validation of estimates that are generated in a bottom-up fashion against official aggregates is a first-order approach to quantifying potential errors, the specific case under examination—namely developing countries with sparse and infrequent collection of information—is characterized by a substantial degree of uncertainty.

First, we have shown that our approach is likely to capture a substantial share of the electrification occurring through the expansion of national grids or larger-scale decentralized systems, but we are likely unable to detect smaller-scale solutions, such as solar home systems and stand-alone diesel generators. Yet, the deployment of these is rapidly gaining pace,[42] and it has been estimated[13] that these could cover around one-fourth of new connections until 2030. While these limited-scale solutions are excluded from the definition of energy access that we explicitly adopt in this paper (consistent with the account provided by the IEA[65]), they could nevertheless represent a first step up the energy ladder, for instance, by saving household costs for kerosene. In turn, at a later stage, savings can be spent on larger-scale systems or to cover national grid connection charges.[45,46]

Second, our approach is weak in distinguishing households that live "under the grid" and yet are lacking access to electricity, and these—particularly in peri-urban areas—represent a significant share of the population.[66] The spatial resolution of 30 m of settlement data only allows for an assessment of settlements where the infrastructure necessary to provide electricity access is lacking. Thus, a caveat is that our estimates measure the infrastructural dimension of electricity access, more than the policy- and financing-related issues that governments and electrification programs must tackle to enable new connections of households living in the proximity of the grid but facing financial and behavioral barriers.[67]

Finally, nighttime light data largely capture radiance between 0:00 and 4:30 a.m., when most residential indoor lights are turned off. Thus, the approach is effective in those settlements where at least minimal amounts of street or public lighting are available.[68] For these reasons, our estimates are correctly interpreted only if they are considered a cheap, rapidly updated geospatial indicator of electricity access to provide snapshots of the access situation in a province or in a country rather than precise estimates of the share of households benefiting from access within a specific village or settlement. Thus, the approach is not meant to replace field data-collection efforts but rather to provide a valuable complement to these efforts. For instance, properly validated satellite-based estimates could help overcome issues of statistical growth when no or infrequent data collection is carried out.

DISCUSSION

Inequalities in Recent Electrification Revealed

Datasets of satellite-based nighttime lights and population distribution allow for analysis of electrification at scales not previously

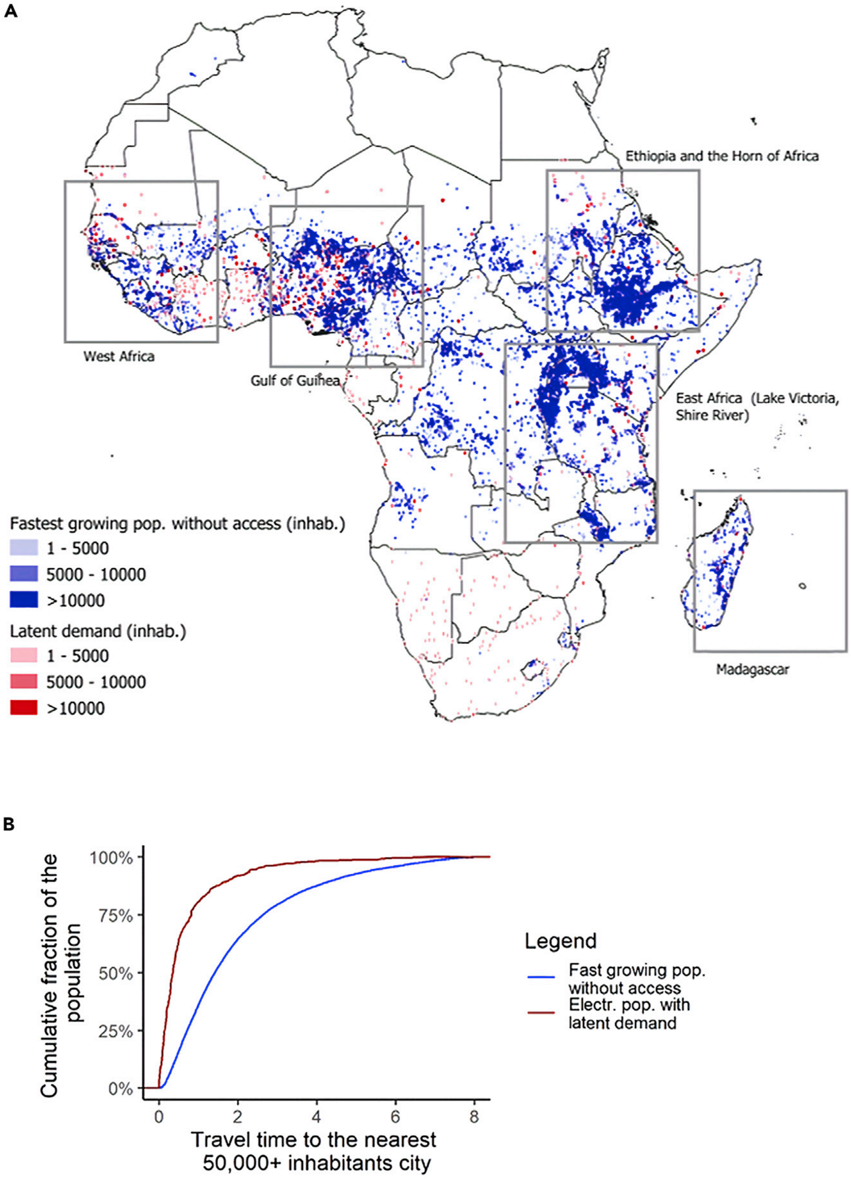

Figure 5. Hotspots of Growing Populations without Access and Future Latent (Unmet) Electricity Demand

(A) Map of hotspots in sub-Saharan Africa where rural and urban access hotspots are categorized separately as the top 10% of the respective spatial distributions across all provinces. Urban and rural latent demand hotspots are defined as areas with electrification above 50% but an estimated consumption level below the 25th percentile of the distribution.

(B) Empirical cumulative distribution curves of the fraction of people without access as a function of remoteness to urban areas in the identified hotspots. The x axis describes the travel time to the nearest 50,000+-inhabitant city in each country derived from Weiss et al.[59] The y axis describes the cumulative fraction of the population of the hotspot living at a travel time equal to or smaller than the corresponding x value. The curves thus describe two dimensions of inequality, namely both between and within the selected hotspots.

possible and benefit from frequent updates from remotely sensed measurements. We demonstrate that a dataset derived from publicly available global satellite imagery can accurately detect electric light at sub-national scales in sub-Saharan Africa and, more importantly, that light intensity can proxy the tier of residential electricity access, allowing for an estimation of inequalities in electricity supply, use, and reliability beyond binary access indicators. The study provides evidence that these analyses can complement existing survey-based assessments, particularly for regions where data are scarce or sporadically collected or where there may be inconsistencies in existing data sources. Moreover, unlike household surveys, the approach illustrated here captures rapidly accelerating electrification and changing population settlement patterns in near real time. The main issues identified are summarized in Table 3 together with their spatial extent and magnitude. Refer to Table S2 for an ISO (International Organization for Standardization) codebook of country names.

We highlight that vast disparities characterize electricity access and use within sub-Saharan African nations. In particular, our analysis helps identify and monitor regions where electricity infrastructure provision is not keeping pace with population growth (such as in large parts of Central Africa and of the Sahel), where a high density of electricity access deficit exists (in Ethiopia, the Gulf of Guinea, and the countries surrounding Lake Victoria in East Africa), or where use remains very low despite relatively high nominal access levels (such as in rural Ghana and Kenya or in urban Ethiopia). These results suggest that, even under a scenario where universal access in terms of availability of electricity supply is achieved, inequalities may persist, undermining the achievement of several of the SDGs, and potentially driving internal migration. Recent literature[69–74] has highlighted how dimensions other than physical access to electricity, such as reliability, have important impacts on the benefits of access, particularly for small and medium businesses that drive much of the growth in developing countries.[52,75] The use of light-intensity data to derive metrics related to the electricity access tier, as done here, can thus also illuminate important qualitative dimensions of electricity access.

Electricity access and use are key components of a broader multi-dimensional concept of poverty. Where there are regions of large unmet electricity demand, these are likely to correlate with those deprived of other key infrastructural services for decent living, such as sanitation (2.3 billion lacking access)[76] and internet connectivity (nearly 4 billion without access).[77] Not only is a lack of access likely to stunt

Table 3. Summary of the Main Issues Identified, Their Spatial Extent, and Their Magnitude

Issue	Regions	Estimated Affected Population (Million)
High-density electrification deficit hotspots (local access level < 25%)	large parts of East Africa (MWI, UGA, BDI, RWA, SSD, TZA, and MDG) and Central Africa (CAF, TCD, and COD); specific areas in MLI, BFA, and ZWE	300
"Under the grid" electrification deficit hotspots (local access level > 50%)	several countries in West Africa (SEN, GHA, CIV, southern NGA, and eastern CMR); specific provinces in southern KEN, central ZMB, southern NAM, and northern SDN	77
Growth in population without access (2014–2019)	most provinces of ETH, DRC, and COD; large parts of UGA, BDI, and TCD; vast areas of the Sahel	50
Low (tiers 1 and 2) electricity use despite high local access level > 50%	large parts of West Africa (GHA, CIV, SEN, and GAB) and Southern Africa (ZAF and BWA); specific areas in KEN, TZA, COD, UGA, MWI, SDN, CMR, AGO, and NAM	70

Three-letter ISO code labels are as follows: AGO, Angola; BDI, Burundi; BEN, Benin; BFA, Burkina Faso; BWA, Botswana; CAF, Central African Republic; CIV, Côte d'Ivoire; CMR, Cameroon; COD, Democratic Republic of the Congo; COG, Republic of the Congo; ERI, Eritrea; ETH, Ethiopia; GAB, Gabon; GHA, Ghana; GIN, Guinea; GMB, Gambia; GNB, Guinea-Bissau; GNQ, Equatorial Guinea; KEN, Kenya; LBR, Liberia; LSO, Lesotho; MDG, Madagascar; MLI, Mali; MOZ, Mozambique; MRT, Mauritania; MWI, Malawi; NAM, Namibia; NER, Niger; NGA, Nigeria; RWA, Rwanda; SDN, Sudan; SEN, Senegal; SLE, Sierra Leone; SOM, Somalia; SSD, South Sudan; SWZ, Swaziland; TCD, Chad; TGO, Togo; TZA, United Republic of Tanzania; UGA, Uganda; ZAF, South Africa; ZMB, Zambia; ZWE, Zimbabwe. Also see Table S2.

progress toward other development objectives, but households living in regions deprived of such basics are also more vulnerable and likely to lack adaptive capacities, essential for reducing risk from natural hazards and climate-change impacts,[60,78] as targeted by SDG 13. Mobile technologies and information services are so pervasive that access to electricity and a smartphone, often achieved long before basic sanitation, opens the possibility of not only life improvements but also vulnerability reduction through banking, health services, insurance, agricultural training, trading, and electoral and social services.

Potential of Achieving Full Electrification by 2030

According to our high-resolution estimates, electricity access in sub-Saharan Africa has grown significantly over the last 6 years such that >115 million people are newly electrified. This development resulted in a 4.7-p.p. increase in the regional electricity access level (from 42.2% to 46.9% of the population) despite strong demographic changes (with about 145 million additional people) between 2014 and 2019. However, if electrification rollout in the coming decade keeps the same pace observed in the 2014–2019 period (with an average 22 million new electrified people per year), the regional population grows according to the most recent estimates of the United Nations Population Division[79] (thus reaching 1.4 billion in 2030), and the share of new population that is born without access is assumed to be proportional to the regional electricity access level (see the Experimental Procedures), then the regional access level in 2030 will be only 62.5% (16 p.p. above today's level). Thus, to fulfill SDG 7's indicator 7.1.1, progress must ramp up immediately for the coming decade. On average, this implies that almost 75 million people need to gain access each year until 2030, as compared with the average of 22 million per year over the period 2014–2019.

The underlying trends analyzed in this paper reveal that additional dimensions and dynamics must be considered. First, urban and rural areas are changing at different rates in both electrification rollout and demographic terms. Electrification has moved faster in rural (5.7 p.p. of growth between 2014 and 2019) than in urban areas (4 p.p. of growth between 2014 and 2019) in relative terms, yet the bulk of progress took place in urban settlements (75 million of the total 115 million who gained access are urban dwellers). Cities are growing rapidly, with the urban population having risen from 540 to 615 million over the 6-year period analyzed. In turn, high population density and existing distribution infrastructure make it easier and more affordable to increase electricity access in urban areas.

On the other hand, the definition of SDG 7 makes only loose mention ("reliable energy services"[80]) to the effective electricity access quality or to specific power availability targets. Our analysis shows that even among households that currently benefit from electricity access, particularly in rural areas, only a fraction benefits from at least tier 3 access, a threshold below which it is challenging to power continuous or medium appliances such as refrigerators or provide air cooling. Previous studies based on computer models have quantified the investment for bridging the electricity access gap in the region[81–86] and have shown that there is an abundance of energy resources and local generation solutions, which are technically sufficient to guarantee universal modern energy access in sub-Saharan Africa. However, the required investments and the optimal technology split between national grid connection and decentralized solutions are highly dependent on the modeling assumptions[87] (including the level of risk perceived by private players[88] involved in electricity access infrastructure investment) and the assumed demand levels, which—as we have shown—needs substantially more consideration in planning toward SDG 7.

Implications for Decision Makers

Sub-Saharan Africa is already witnessing rapid urbanization. Our analysis suggests that providing secure, sustainable access even to urban centers with relatively high population densities may be increasingly challenging. Infrastructure expansion in slums is particularly tricky because of the geographical configuration of such areas; the legal, regulatory, and market risks for investors;[47,89–91] and the low ability to pay of the peri-urban poor.[48,92–94] Focused efforts on identifying best practices, lessons learned, and barriers in urban electrification rollout are urgently needed to aid implementation in key locations that are falling behind.

Policies aiming to achieve the SDG 7 target of universal electricity access need to facilitate longer-term planning and provide for a decent level of electricity service to all beyond just connections. This requires planning for infrastructure expansion that is commensurate and scalable to subsequent demand growth as incomes rise[95–97] (M. Poblete-Cazenave and S.P., unpublished data). Acknowledging the significant geographical dimension to electricity access puts remote regions at a distinct disadvantage.[98] However, high grid connection charges, along with other barriers,[99] can limit the expansion of access, even for households under reach of existing national grids. Overcoming these barriers requires smart payment schemes and innovative business models.[100] Challenges in extending central grid infrastructure to remote regions have resulted in an increasing market penetration of decentralized energy solutions that are forecast to be the least-cost option to bring electricity to households currently without access in many locations across the continent.[84,101,102] Care is required in the sizing of such distributed solutions because if underscaled, they may be insufficient to meet growing demand from different sectors and thus exacerbate inequalities, while an oversizing could make the system economically unsustainable for both users and the companies managing the infrastructure.[103]

Finally, universal access to modern, affordable, reliable, and sufficient energy shows key interlinkages with most SDGs,[104] and in particular education (for studying at night, information, and communication), health (vaccine storage and medical devices), hunger (food storage and greater nutritional diversity of fresh goods). With regard to SDG 13 on climate action,[105] previous research has shown that while universal electricity access has very little impact on global greenhouse gas emissions,[106,107] the electricity requirements for adaptation are instead substantial[62,108] and thus need greater consideration in electrification planning. An insufficient supply might leave populations with electricity access exposed to droughts and heat waves, whereas a more resilient and abundant supply could provide the means for essential services, e.g., water pumping and cooling.

Conclusion

This paper analyzed 6 years of spatially explicit electrification data for sub-Saharan Africa on the basis of an open-access cloud-computing framework using remotely sensed sources. Our estimates are consistent with previous global analyses, but crucially we show wide hidden disparities of changes in access and tier-measured electricity use within countries and provinces. The analysis confirms that recent progress toward universal electrification has been made, but it shows that nominal access levels are inherently limiting. Focusing solely on maximizing nominal access levels might even jeopardize the achievement of other SDGs because connections alone do not ensure actual use of electricity, reduce related inequalities, or help achieve co-benefits across several other SDGs.

Crucially, we find that among those with access to electricity, a vast distribution across access quality tiers exists. We also find that in some countries, where recently strong electricity access growth (the main ones being Kenya and Ethiopia) has been reported, the estimated final use remains very limited among newly electrified households. This is consistent with previous studies finding, for instance, that per-grid-connected domestic customer power consumption in Kenya has declined by almost 70% over the last 10 years because of the very low consumption of newly connected customers[49] and that recent large-scale national grid electrification investment in Rwanda has hitherto led to very low use of newly connected households, with a median of 6 kWh/month and limited appliance uptake.[71]

Together, these results raise questions over the effectiveness of those electrification plans and suggest the need to critically evaluate the success of electrification programs beyond their role in boosting the national electricity access statistics. This implies that large gaps in unmet demand might remain both across and within countries even under a scenario of universal electrification by 2030. In turn, this unequal service provision could have serious implications for achieving nearly all SDGs, including SDG 10 that specifically targets the reduction of inequalities, and SDG 13 since energy poverty limits the capacity of households and productive facilities to adapt to a changing climate,[62,109] constrains access to health and education services,[69,110] and might affect food security.[111] Moreover, we estimate that if the electrification pace witnessed in the last 6 years remains constant, in 2030 the progress to full electrification in sub-Saharan Africa would be only about 63%, leaving 520 million still without access. This means that progress must ramp up in the coming decade, and on average 75 million people must receive access to electricity each year until 2030. We have shown that the strong demographic growth and migration flows play a very significant role in this process.

We argue that electrification projects and monitoring initiatives need to consider a broad array of aspects and implications of electrification and not focus exclusively on maximizing electric connections. Insufficient power might leave many households without the capacity to benefit from productive uses of energy or to adapt to new conditions, even when they are formally classified as with electricity access. To this end, properly validated satellite-based estimates can be an effective, readily updated, and low-cost means of complementing surveying efforts targeted at tracking electrification progress and planning its expansion.

EXPERIMENTAL PROCEDURES

Resource Availability

Lead Contact

For queries related to this article, please contact giacomo.falchetta@feem.it.

Materials Availability

Not applicable to this study.

Data and Code Availability

The accession number for the data reported in this paper is Zenodo: 3737830. Computer code and input data for replicating or updating the analysis and the figures are hosted at https://github.com/giacfalk/inequality_electrification_SSA.

Data Inputs and Processing

The Google Earth Engine platform[40] was used to process spatially explicit imagery and extract data, which was used for calculating trends and inequality measures and producing plots in the R scientific computing environment. The Data and Code Availability section links to the repository that hosts the JavaScript and R and allows for results reproduction, alteration of parameters for sensitivity analysis, and further improvements. All the datasets used in the analysis are openly accessible and retrievable under the references reported in Table S3, ensuring full replicability of the analysis.

The data sources include VIIRS (Visible Infrared Imaging Radiometry Suite) stray-light corrected monthly composites for 2014–2019,[31] the High-Resolution Settlement Layer (HRSL) 30-m ambient population,[33] and the Global Human Settlement Layer (GHSL)[114]—including built-up areas and settlement type layers—used for rural and urban areas classification. We selected the HRSL as the reference population dataset because it represents the highest-resolution publicly available Africa-wide gridded population layer. This refers to year 2015 and is based on recent census data and high-resolution (0.5 m) satellite imagery from DigitalGlobe. The Connectivity Lab at Facebook developed the settlement extent data by using computer vision techniques to classify blocks of optical satellite data as settled (containing buildings) or not. The Center for International Earth Science Information Network used proportional allocation to distribute population data from sub-national census data to the settlement extents. Note that as of late 2019, the HRSL lacks information for four countries in the Horn of Africa: Ethiopia, Somalia, Sudan, and South Sudan. We relied on the 250-m-resolution 2015 GHSL data, downscaled it to a 30-m resolution imposing a constraint such that the sum of the pixels remains constant after the downscaling (to avoid generating biased population counts due to the interpolation process), and mosaiced it over the HRSL for the four countries in question to produce a comprehensive 30-m-resolution layer for sub-Saharan Africa. Refer to Simulation of Demographic Growth and Migration Trends for a description of how the HRSL population counts have been reprojected to previous or following years.

National electrification levels for comparison with our estimates were drawn from the ESMAP-World Bank Tracking SDG7 portal, i.e., the data underpinning the *Tracking SDG7: Energy Progress Report 2019*,[2] the *Atlas of the Sustainable Development Goals* from the World Development Indicators database,[15] and the *Africa Energy Outlook 2019*,[13] whereas province-level figures were drawn from an array of field surveys through the DHS Program STATcompiler[41] for sub-national benchmarking. For validating electricity access tiers, World Bank-ESMAP MTF surveys for households were retrieved from the Microdata Library for countries with recent information on the distribution of consumption across urban and rural areas, and this information was used for classifying households across consumption tiers. For defining countries and provinces, we adopted the global administrative boundaries (GADM) dataset v3.6 as the standard.[112]

Identification of Urban and Rural Areas

Urban and rural settlements were identified at the grid-cell level according to the GHS-SMOD 2015 settlement classification and were classified as urban (GHS-SMOD $\geq$ 2), rural (GHS-SMOD $\leq$ 1), or not inhabited (GHS-POP = 0). Classification details are detailed in Pesaresi et al.[113] In general, urban areas included both cities or large urban areas, i.e., "contiguous cells with a density of at least 1.500 inhabitants per km^2 or a density of built-up greater than 50% and a minimum of 50.000 inhabitants," and towns and suburbs or small urban areas, namely "contiguous grid cells with a density of at least 300 inhabitants per km^2 and a minimum population of 5.000 inhabitants." The inhabited pixels that did not satisfy these criteria were marked as rural areas. To assess the consistency of the classification criteria with the country-level urban population share reported by the World Bank[114] for 2018, we summed the total GHS-POP 2015 population in cells classified as urban and divided it by the sum of total population. This yielded a regional value of 0.42, which is very much in line with the fraction of urban population in sub-Saharan Africa: 0.4. An exploration of the county-level predicted urbanization levels revealed that consistency with the figures of the World Bank and UN Population Division is mixed across countries. Nevertheless, we deem the remotely sensed classification of the GHSL more homogeneous than the national figures provided by statistical offices, for which the definitions vary across countries.

Simulation of Demographic Growth and Migration Trends

To estimate the role of demographic growth and migration on the electrification process over the 2014–2019 period considered and to implement it into the HRSL gridded population dataset, we adopted an approach relying on the official statistics from World Bank data over the yearly country-level population growth rate and share of the total population living in urban areas. Algebraically, this can be expressed as

$$\mathrm{pop}_t^i = U\left(\mathrm{pop}_{t-1}^{i\ \mathrm{urb}}\left(1+\mathrm{PGR}_t^c\left(1+\Delta\mathrm{URB}_{t-1}^{t\ \ c}\right)\right),\mathrm{pop}_{\mathrm{t}-1}^{i\ \mathrm{rur}}\left(1+\mathrm{PGR}_t^c\left(1+\Delta\mathrm{RUR}_{t-1}^{t\ c}\right)\right)\right), \qquad \text{(Equation 1)}$$

i.e., as the union raster layer of the urban and rural populations layers in year t, each calculated as the product between the population in each cell i and the population growth rate (PGR) in the same year in each country c weighted by the change in the share of urban or rural population with respect to the previous year in each country c. The approach allows one to integrate the heterogeneity in the demographic change across urban and rural areas and across each country. The main limit is that, within each country, population dynamics are homogeneous across all urban and rural areas.

Estimation and Validation of Electricity Access Levels

To estimate electricity access, we calculated the yearly median radiance value in each pixel of the Suomi National Polar-orbiting Partnership-VIIRS monthly composites within the Google Earth Engine platform for each year between 2014 and 2019 by using Google Earth Engine. Then, to remove calibration noise and ephemeral lights as discussed in the relevant literature,[115,116] we applied a lower-bound noise floor (0.25 μW cm^{-2} sr^{-1} until 2016 and 0.35 μW cm^{-2} sr^{-1} from 2017; see Falchetta et al.[26] for justification of the threshold values choice). We proceeded by subsetting populated pixels with stable positive radiance and identifying them as electrified, whereas we classified populated pixels with zero radiance as not electrified. We calculated zonal statistics within each administrative unit to obtain the sum of the population with access to electricity and total population counts. We calculated the ratio between the two numbers to derive local electricity access levels. To conclude, we validated the estimated electrification levels against an array of sources providing official electrification statistics, as shown in Table 1.

Measurement of Electricity Access Inequality

We assessed inequality by calculating the Gini index of electricity access among urban and rural areas in each province within each country. The Gini index measures inequality and ranges from 0 to 1, where 0 expresses perfect equality and 1 expresses extreme inequality. In this calculation, provinces were weighted by their (urban or rural) population as a share of the national (urban or rural) population for the Gini index to reflect inequality in terms of the relative number of people in each region. A country with equal electrification levels across its provinces is in fact not equal per se, as equality is contingent on the distribution of the population across provinces. Repeating this procedure for the data between 2014 and 2019 allowed us to calculate the change in the distribution over the 6-year period examined, as well as the corresponding change in the Gini index of within-country residential access tier inequality. The index is defined as

$$G_i = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}\left|p_{ic}x_i - p_{ic}x_j\right|}{2n\sum_{i=1}^{n}p_{ic}x_i}, \qquad \text{(Equation 2)}$$

where x is the electricity access level and p is the share of population of province i in country c, j is all the remaining provinces in the country, and n is the total number of provinces. The definition of the Gini index is strictly related to that of the Lorenz curve,[117] defined as a continuous piecewise linear function $L(F)$, where F defines the cumulative fraction of the population in the distribution (and is usually represented on the horizontal axis) and L represents the cumulative portion of the total response variable (in this case electricity access) and is plotted on the vertical axis.

Estimation and Validation of Electricity Access Tiers

On the basis of the distribution of the quartile values of non-zero light radiance across sub-Saharan African countries, we defined four tiers of residential access to electricity for those estimated to live in areas with electricity access and set thresholds at the median value of each quartile distribution. To account for the strong urban-rural discontinuity in terms of lighting, we conducted this separately for urban and rural settlements. We validated the distribution of population across the four tiers against survey data collected from ESMAP in three countries (Rwanda, Ethiopia, and Zambia) where this information is available. These surveys provide a measure of the distribution of households across access tiers in both urban and rural areas. Our estimates thus match the World Bank MTF.[10] Here, we considered MTF tiers 0 and 1 and tiers 4 and 5 jointly because MTF tiers 1 and 5 (<0.2 kWh/household/day and >8.2 kWh/household/day, respectively) correspond to electricity consumption levels that are either too high or too low to be distinguished from a lack of access or an abundant and reliable level of access.

DHS Survey Data Collation and Regression Analysis

To offer a further layer of validation and estimate the relationship between recent progress, the estimated access tiers, and an array of information collected through household surveys, we matched province-level statistics on the distribution of wealth across households and information about the share of households owning four basic electrical appliances. These were mostly DHS surveys carried out by the United States Agency for International Development in the 2014–2019 period analyzed. The survey data are provided at a province level where the province name identifies each observation. Province names are fuzzy merged with the province names reported in the GADM shapefiles in the R scientific computing environment and linked through a survey-year/estimate-year matching. We then performed regression analysis via OLS (ordinary least squares) with the inclusion of country fixed effects to identify statistical associations.

Hotspot Identification

To identify hotspots—areas with the fastest-growing number of people without access—we generated a regular 10-km grid over the shapefile of sub-Saharan Africa. Within each 1-km grid cell, we estimated electrification for both 2014 and 2019. We then subtracted the two layers to obtain the difference between the two years and summed the number of people without access within each 10-km grid cell. Finally, we filtered the grid cells in the top decile (i.e., above the 90th percentile of the distribution) to determine which were classified as hotspots. To assess the location of areas where it was plausible to assume that significant latent demand existed, we calculated the electrification level and the mean tier of consumption within each 10-km grid cell. Then, only those grid cells that exhibited an electrification level of at least 50% and an estimated mean access tier lying below the 25th percentile of the distribution were retained. To explore the significance of proximity to urban areas for the identified hotspots, we plotted pixel-level empirical cumulative distribution curves of the population living in the identified hotspots against the travel time to the nearest 50,000+-inhabitant city. We derived the latter information from Weiss et al.[59] and calculated it by exploiting a friction surface raster layer that expressed at each pixel the average time to move by 1 m given the local road and railway infrastructure, terrain characteristics, and administrative boundaries.

Calculation of Electrification Rollout Requirements

To estimate the road to full electrification by 2030, we referred to the most recent estimates of population growth from the United Nations Population Division.[79] We assumed that the newly added population was split among electrified and non-electrified households proportionally to the electricity access rate in 2019. Thus, we estimated the number of people without access in 2030 if the electrification rollout were to keep the same pace observed in the 2014–2019 period as

$$\mathrm{noacc}_{2030} = \left(\mathrm{noacc}_{2019} + \left(\mathrm{pop}_{2030} - \mathrm{pop}_{2019}\right) \times \left(1 - \mathrm{el\ .\ rate}_{2019}\right)\right) - 20 \times 10, \quad \text{(Equation 3)}$$

where 20 is the average number of people gaining access to electricity yearly and 10 refers to the number of years until 2030. To estimate the number of people who would need to gain access every year, we instead adopted the following formula:

$$\overline{\mathrm{newacc}_t} = \frac{\left(\mathrm{noacc}_{2019} + \left(\mathrm{pop}_{2030} - \mathrm{pop}_{2010}\right) \times \left(1 - \mathrm{el.\ rate}_{2019}\right)\right)}{10}. \quad \text{(Equation 4)}$$

SUPPLEMENTAL INFORMATION

Supplemental Information can be found online at https://doi.org/10.1016/j.oneear.2020.03.007.

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AUTHOR CONTRIBUTIONS

Conceptualization, G.F., S.P., O.D., E.B, and S.C.P.; Data Curation, G.F. and O.D.; Formal Analysis, G.F; Visualization, G.F.; Writing, G.F., S.P., O.D., E.B., and S.C.P.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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