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Planning sustainable electricity solutions for refugee settlements in sub-Saharan Africa

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An inadequate understanding of the energy needs of forcibly displaced populations is one of the main obstacles in providing sustainable and reliable energy to refugees and their host communities. Here, we provide a first-order assessment of the main factors determining the decision to deploy fully renewable mini-grids in almost 300 refugee settlements in sub-Saharan Africa. Using an energy assessment survey and publicly available traditional and earth observation data, we estimate a total electricity demand of 154 GWh yr⁻¹. This figure includes lighting, air circulation and phone charging for 1.15 million households and the estimated demand of almost 59,000 microbusinesses and around 7,000 institutional loads. Using a set of techno-economic modelling tools, we thus compute a corresponding upper-bound total up-front cost of providing electricity access of just over US\$1 billion. Deploying solar photovoltaic mini-grids instead of diesel implies avoiding greenhouse gas emissions for 2.86 MtCO_{2e} over 20 years.

The main focus of humanitarian organizations assisting refugees is on life-saving needs, starting with protection, health, food, water and shelter. Energy provision in forcibly displaced population settings is generally limited to the minimum requirement for essential services and critical operations of humanitarian actors. It also mostly depends on stand-alone diesel generators. According to estimates by the Moving Energy Initiative, ~80% of displaced populations in camps burn biomass such as firewood for cooking and ~90% have limited or no access to electricity¹. The uncertainty around how long displacement settings will remain open, together with a shortage of funding and technical expertise, help explain the current situation. The complexity of the decision-making process leading to the development of energy infrastructures in the hosting country and a poor understanding of the energy needs of refugees add to the difficulties associated with deploying sustainable energy solutions for refugees^{2–5}.

Access to sustainable and reliable energy in displacement settings is receiving increasing attention as a fundamental human need and an enabler of the longer-term development of refugees and their host communities. In addition to environmental benefits, clean electricity access in refugee settlements is associated with improved health, water, education services, security, gender-based violence reduction and opportunities for income-generating activities⁶. As a recent example, the presence of a solar-powered mini-grid in the Kalobeyi settlement (Kenya) increased the number of informal businesses run by refugees and host communities, with cooled beverages vendors, phone charging spots, hair-dressers and many other enterprises sprouting. A branch of a local bank was also opened inside the settlement⁷.

Acknowledging the need to move past pilot projects and scale up the efforts, overarching initiatives such as the Clean Energy Challenge and the Global Platform for Action (GPA) on sustainable energy in displacement settings (<https://www.humanitarianenergy.org/>) have emerged³. Nevertheless, if the goal of deploying sustainable energy solutions is obtaining long-term impacts⁴, it is crucial to address another of its main obstacles: the lack of quality and accessible data. Together with humanitarian and development

organizations, the academic literature has repeatedly highlighted the need to improve the collection, management, analysis and sharing of energy data in the humanitarian context as a means to foster and shape a significantly improved, collective response^{5,8,9}. Achieving access to sustainable energy relies on interinstitutional cooperation, local governments, donors and the private sector. For this reason, access to reliable data is essential to understand the full range of the energy needs, to design and plan effective evidence-based interventions and to coordinate the release of financial aid.

One of the working areas of the GPA¹⁰ addresses the need for harmonized data practices to track, prioritize and support progress in energy access of displaced communities. Preliminary work has outlined the core indicators for global and project-level data that should enter a common framework for sustainable energy data collection, analysis and sharing. Other initiatives include the Energy Monitoring Framework (<https://eis.unhcr.org/home>), tracking energy programmes funded by the United Nations High Commissioner for Refugees (UNHCR) and the Moving Energy Initiative (<https://www.chathamhouse.org>), promoting learning by doing via pilot projects (in Burkina Faso, Kenya and Jordan). The projects Humanitarian Engineering and Energy for Displacement (<http://heed-refugee.coventry.ac.uk/>), Renewable Energy for Refugees (<https://data.humdata.org/organization/practicalaction>) and Energy Solutions for Displacement Settings (https://energy-pedia.info/wiki/Energy_Solutions_for_Displacement_Settings), also share evidence from energy interventions in Nepal, Jordan and a few African countries, including sensor data and surveys about energy usage.

Despite these initiatives, the information around energy supply, needs and costs in displacement settings remain scarce, fragmented and primarily focused on the progress achieved rather than the work ahead. To contribute filling such a knowledge gap, this work's findings are collected in the Refugee Settlements Electricity Access Database (RSEA DB). Intended to be openly shared with the academic community and other shareholders, the RSEA DB includes detailed and harmonized quality data on the electricity needs, potential technical solutions and associated costs for almost 300

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refugee settlements in sub-Saharan Africa (SSA). The data collection process, the methods designed to estimate unavailable information and size suitable technical solutions are briefly described. Then the focus is on what one can learn from these data. Here, an estimation is derived of the effort needed to deliver sustainable electricity access to all the observed refugee settlements. Furthermore, the data can be used, in combination with earth observations, to address a broader range of research questions (the example given here concerns the interaction of refugees with the host community) and to disseminate knowledge. Consistently, a vision is laid out for open-access humanitarian data to support further research and help humanitarian agencies to achieve Sustainable Development Goal 7 (SDG7).

The RSEA DB

Two features characterize the RSEA DB: the ability to integrate traditional and new data sources to create holistic, standardized and contextual information about sustainable electricity access in refugee settlements and the goal to share these data across different shareholders.

The first step in building the RSEA DB was to create a consistent and complete list of the existing refugee settlements in SSA (although they are part of the population of concern for UNHCR, the RSEA DB does not track internally displaced persons or asylum seekers). Data collection included traditional sources (by national statistical offices, government agencies, international organizations and in situ reporting) that were cross-checked for consistency and new data sources such as satellite imagery and spatial data infrastructures. For instance, collaborative, crowdsourced data (OpenStreetMap) were used to fill the data gaps on the geographical locations of settlements.

Information on the social context and the settlements' electricity needs was particularly difficult to find. Public sources for this type of data are limited and often outdated^{5,8}. For example, while the population per settlement was mostly available, other relevant data, such as the presence of public or institutional loads (health and education facilities, police stations and offices) and productive ones (small businesses), was found for nine settlements only. Interviews with humanitarian energy experts and other stakeholders were helpful in this regard. On top of this, a primary data collection on current and perspective electricity consumption conducted in Kalobeyi in 2020, proved essential to fill the knowledge gap. The survey data lead to the calculation of the electricity demand and daily load profiles for three types of end-users: households, businesses and institutions. The same results were then scaled to estimate the demand and load profiles for all the other settlements in the database. The characterization of the social context was also estimated from the collected evidence (for details of these processes see Methods).

The social context and the electricity needs included in the RSEA DB should therefore be considered with caution. Kalobeyi is part of a specific programme¹¹ promoting the development of the local economy and an enhanced delivery of services to the refugees and the host community. While this context enabled respondents to the in-person survey to be relatively well informed about their attitudes towards electricity usage, it also makes Kalobeyi not entirely representative of other refugee settlements in SSA. Furthermore, refugees that have been displaced for different lengths of time, those that are allowed or not allowed to work or that have different backgrounds, income levels and prior exposure to electricity access are expected to present a diverse demand for energy services^{6,12–14}. These aspects are not yet captured by the RSEA DB.

New data sources were used for the geospatial contextualization of hourly solar irradiation¹⁵ distance to the existing electricity grid¹⁶ and national borders, existing power plants¹⁶, boundaries of the settlements and local population distribution^{17,18} (the last was based on

census data, high-resolution satellite imagery and night-light imagery). Often, these parameters are not easily accessible, especially in their entirety.

The optimal electricity access solution for each refugee settlement (connecting all residential, public and productive loads) was computed using a photovoltaic (PV) mini-grid optimization model^{19,20} under a set of uniform (across settlement) technical assumptions (Methods; Supplementary Table 1) and under a reference electricity demand scenario consistent with the UNHCR goal for universal electricity access²¹. This scenario involves providing tier 2 electricity access; that is, a minimum of 200 Wh d⁻¹ per household²² allowing for basic lighting, air circulation, television and phone charging. In light of the UNHCR's Global Strategy for Sustainable Energy²¹ to promote access via decentralized clean electricity generation, this study focused on fully renewable mini-grids²³—considering also the high population density and the presence of anchor loads. The optimal size of the solar PV and battery storage capacities for each mini-grid (one per settlement) was input into the RSEA database together with the estimated up-front capacity costs, the levelized cost of electricity (LCOE) and the avoided emissions (Methods)

To illustrate the type of results made available for each refugee settlement, it is worth looking at a specific case. For example, Moyo in Chad, a settlement located >180 km from the grid, hosts an estimated 2,509 households, 127 productive and 15 public loads (median load values for the RSEA DB). It presents an estimated annual electricity demand of 922.4 kWh d⁻¹ and an hourly load profile with a distinctive peak in the evening (Supplementary Fig. 1 and Supplementary Table 2a). The latter is dominated mostly by residential demand, which constitutes 87% of the settlement's daily consumption. By design, similar aggregated load profiles and shares of residential demand characterize all the observed settlements. It is worth noticing that, in contrast with the assumptions behind these results (all households are connected to the mini-grid), only 7% of the respondents to the field survey in Kalobeyi had access to electricity via a connection to a mini-grid. More generally, according to the latest 'Tracking SDG7: Energy Progress Report'²⁴ the electricity access rates for refugees in SSA are between 1% and 25%, depending on the hosting country. The optimal capacity of the solar PV and battery storage system for Moyo is computed at 530 kWp and 1,550 kWh, respectively. The up-front capacity cost of the mini-grid is calculated at US\$2.96 million, the LCOE at US\$0.33 kWh⁻¹ and the avoided greenhouse gas (GHG) emissions at 313 tCO_{2e} yr⁻¹ or 6,258 tCO_{2e} over the lifetime of the project. The last figures derive from computing the avoided annual emissions by using fully renewable electricity instead of running stand-alone diesel generators supplying the same electricity demand.

Several studies have appraised the potential of decentralized renewable systems to power refugee sites; in fact, they focus on single (or a few) settlements only and adopt different, ad hoc modelling approaches^{5,25}. Distinctively, this work takes a macrolevel perspective, whereby the electricity demand, the techno-economic indicators for the optimized mini-grids and the associated avoided emissions, are consistently estimated for all settlements in the region. Taking a macrolevel perspective has two main advantages. First, the availability of the same data across several settlements enables comparisons, cross-evaluations and learning from similar contexts. Second, these data deliver a comprehensive and consistent indication of the scale of the technical, economic and environmental implications of providing electricity access to all settlements in the SSA region (see next section). With the estimated total electricity need, such information is instrumental in building a pipeline of electrification projects and programmes for each country, region or settlement. Humanitarian and development agencies can create ranges of implementation plans and timelines and share them with local governments, donors and the private sector. Additional benefits derive from collecting all information in one open-access

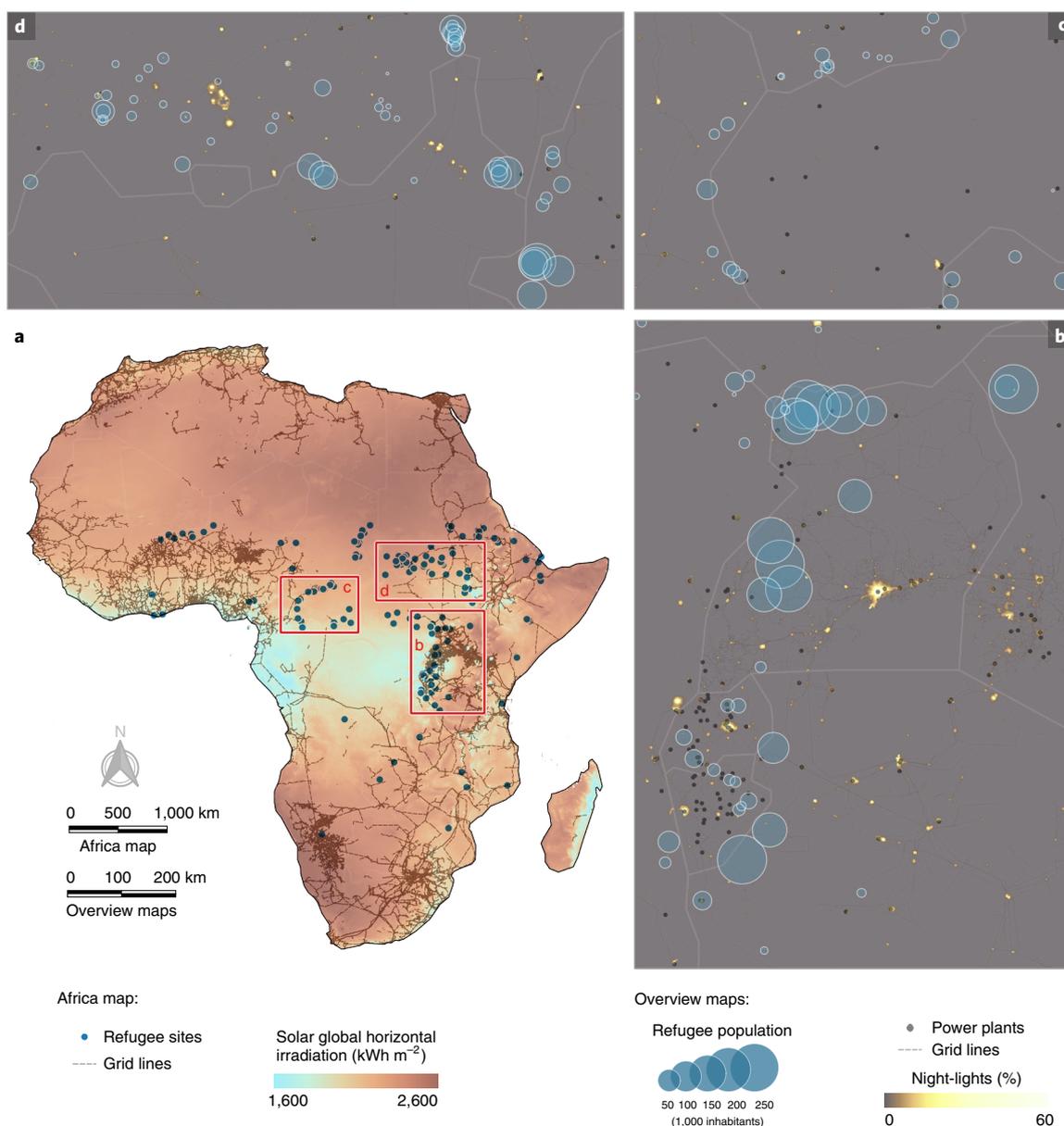


Fig. 1 | Refugee sites in SSA. **a**, The blue spots in the African map indicate the refugee site locations with respect to the solar potential and the electricity grid. **b–d**, Enlarged geographical areas as indicated in **a** with the number of refugees per site indicated by the size of the blue circles. The intensity of night-lights⁵², the existing power plants¹⁶ and the existing and planned electric network¹⁶ (brown lines) are represented in the background to contextualize the location of the refugee sites. The maps were generated using the following data (collected and processed by the authors): solar global horizontal irradiation data (produced and made publicly available by the European Commission—JRC; <https://ec.europa.eu/jrc/en/pvgis>); the geospatial datasets of the electric grid and power plants are compiled by JRC using multiple sources and are publicly available at the JRC Geo-Information System for Renewables catalogue (<https://data.jrc.ec.europa.eu/collection/id-0076>). Country administrative units are from Eurostat (2020) (<https://ec.europa.eu/eurostat/web/gisco/geodata/reference-data/administrative-units-statistical-units/>). Night-time lights data are from v.4 DMSP-OLS 17, produced and made publicly available by NOAA's National Geophysical Data Centre (<https://ngdc.noaa.gov/eog/dmsp/downloadV4composites.html>).

database: data availability for researchers is essential to develop and test new concepts; furthermore it allows the inclusion of new or updated datasets and the integration of the available information into other data sharing tools (section on Integration with earth observations and dissemination).

Providing electricity access to refugee settlements in SSA

The RSEA data indicate that the sub-Saharan region hosts 4.78 million refugees out of 20.7 million worldwide under the UNHCR mandate at the end of 2020. The 288 settlements (203 refugee sites, 18 of which include more than one settlement) are scattered across

23 African nations (descriptive statistics in Supplementary Table 3). As illustrated in Fig. 1 most refugees are located in East and Central Africa (78% and 16%, respectively), with far fewer in Western and Southern Africa (3% each) and 57% of the settlements are within 50 km of national borders. The countries hosting the highest numbers of refugees are Uganda (1.35 million people) and Ethiopia (0.67 million), followed by Sudan, Chad and Kenya, hosting >0.42 million refugees per country. There is also a significant variation in the size of the settlements. The smallest ones are Tegmala in Sudan and Pladama Ouaka in the Central African Republic, with 250 refugees each. The largest ones are in Uganda (Bidibidi hosts

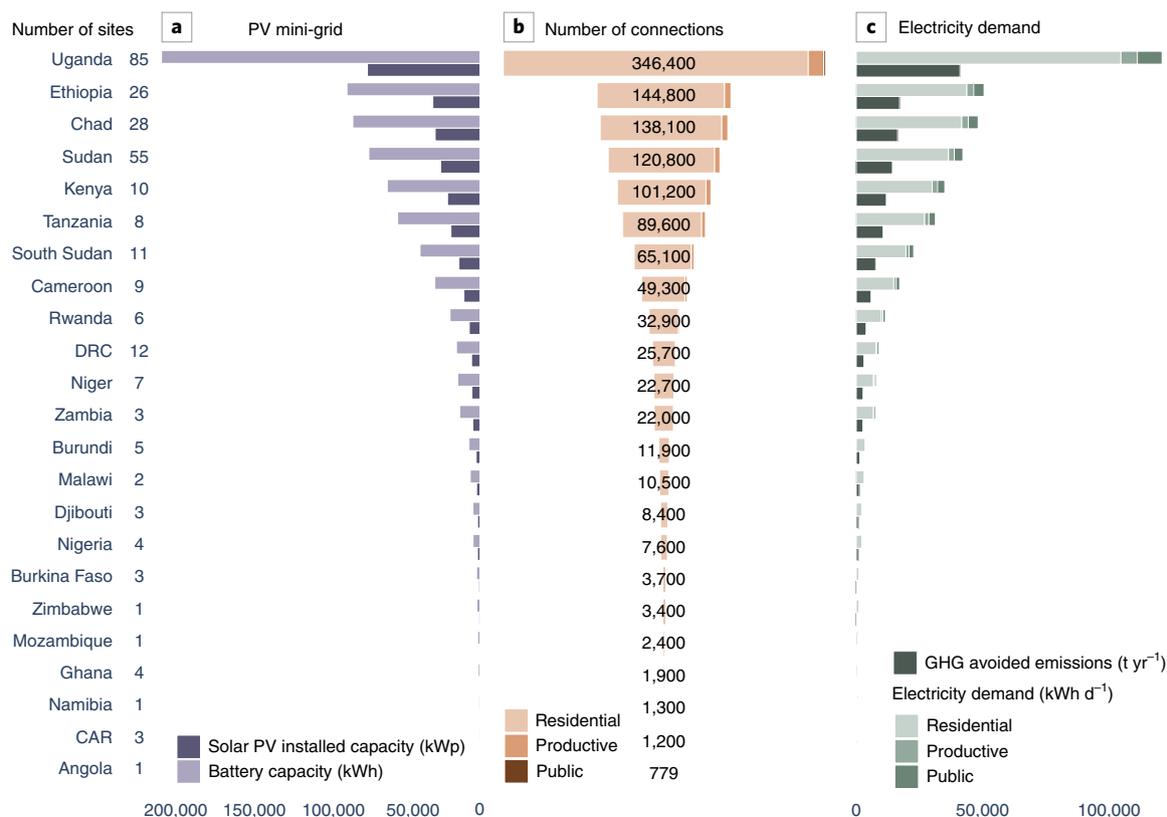


Fig. 2 | Total figures for sustainable electricity access in refugee settlements at country level. **a**, Estimated total PV mini-grid capacity (solar PV and battery capacity). The PV and battery sizes were optimized per settlement on the basis of the site conditions and requirements (Methods) and aggregated at country level. **b**, Estimated number of connections per settlement aggregated at country level. The number of connections per settlement is the sum of residential (number of households), productive (number of businesses) and public (institutional) loads. **c**, Daily electricity demand in refugee settlements aggregated per country. Total electricity demand distinguishes by residential, productive and public (institutional) demand. Estimated avoided GHG emissions in CO_{2e} (by using fully renewable mini-grids) are calculated per settlement and aggregated per country. DRC, Democratic Republic of the Congo; CAR, Central African Republic.

232,733 refugees and Adjumani, 173,645) and in Kenya (Dadaab hosts 236,217 refugees and Kakuma, 155,692). Of all the observed settlements, 48% (139) are >10 km from the electrical network, with distances spanning from <1 km (for 28 settlements) to 747 km for Iridimi in Chad. The availability of solar energy varies with the geographical location and presents seasonal differences; however, most settlements are in a favourable position concerning solar irradiation (the average value is 2,198 kWh m⁻² compared, for instance, with 1,700 kWh m⁻² in the Mediterranean region).

Looking at the aggregated data in the RSEA DB, the total annual electricity demand (sum of annual demand of all settlements) under the reference scenario is ~154 GWh—a breakdown per country is given in Fig. 2. To put this number in perspective, New Zealand, a high-income country with a similar population (4.94 million people), consumed 150 times more electricity in 2020 (39.06 TWh). The total PV capacity to be installed is 247 MWp (including 699 MWh of battery storage). The latter numbers are relatively small compared to the International Energy Agency's projections of PV deployment in Africa (almost 15 GWp per year and reaching 320 GWp by 2040)²⁶. The total avoided GHG emissions are 2.86 MtCO_{2e} over a lifetime of 20 yr. The total estimated up-front capacity cost required to provide electricity to the 288 settlements in the RSEA DB is US\$1.34 billion. While this figure is only a first approximation, it indicates the higher end of the scale of the necessary up-front cost investment—a fully renewable mini-grid presents high up-front investment costs compared to hybrid alternatives. At the same time, several studies comparing the economic lifetime viability^{27–31} of diesel-only, 100%

solar PV and hybrid diesel and solar PV systems, found solar PV options less expensive than diesel-only options. Note that UNHCR, whose 2021 budget for all the activities concerning the SSA refugee programme already amounts to US\$2.65 billion³², counts on hosting countries and development actors to support this effort.

Finally, assuming a 10% discount rate, the average LCOE over the observed settlements is US\$0.31 kWh⁻¹ (Supplementary Table 3), which is aligned with recent contributions^{3,25}. While LCOE values are often used to compare preliminary project assessments, it is worth recalling that they offer little insights on other key economic challenges, associated with financing renewable mini-grids in humanitarian settings or designing business models under which the electricity service can be efficiently provided at an affordable rate for refugees^{6,25,33–35}. To give an idea of the complexity of these issues, affordability considerations alone would require information on current and prospective energy-related expenditures, household incomes and service quality, to name a few. For example, recent estimates^{6,36} indicate that only a minority of the households in the Gihembe, Nyabiheke and Kigeme settlements in Rwanda have a solar home system (received as donation or purchased from retailers). The others spend on average US\$1.05 month⁻¹ on sources of lighting such as candles and batteries^{6,36}. Using the LCOE estimated for the same settlements (an average US\$0.39 kWh⁻¹), the expenditures associated with tier 2 electricity demand would amount to US\$2.32 month⁻¹. Such expenditures correspond, on average, to 4% of the monthly income of a refugee household in the same settlements (which includes direct aid, in the form of cash and voucher

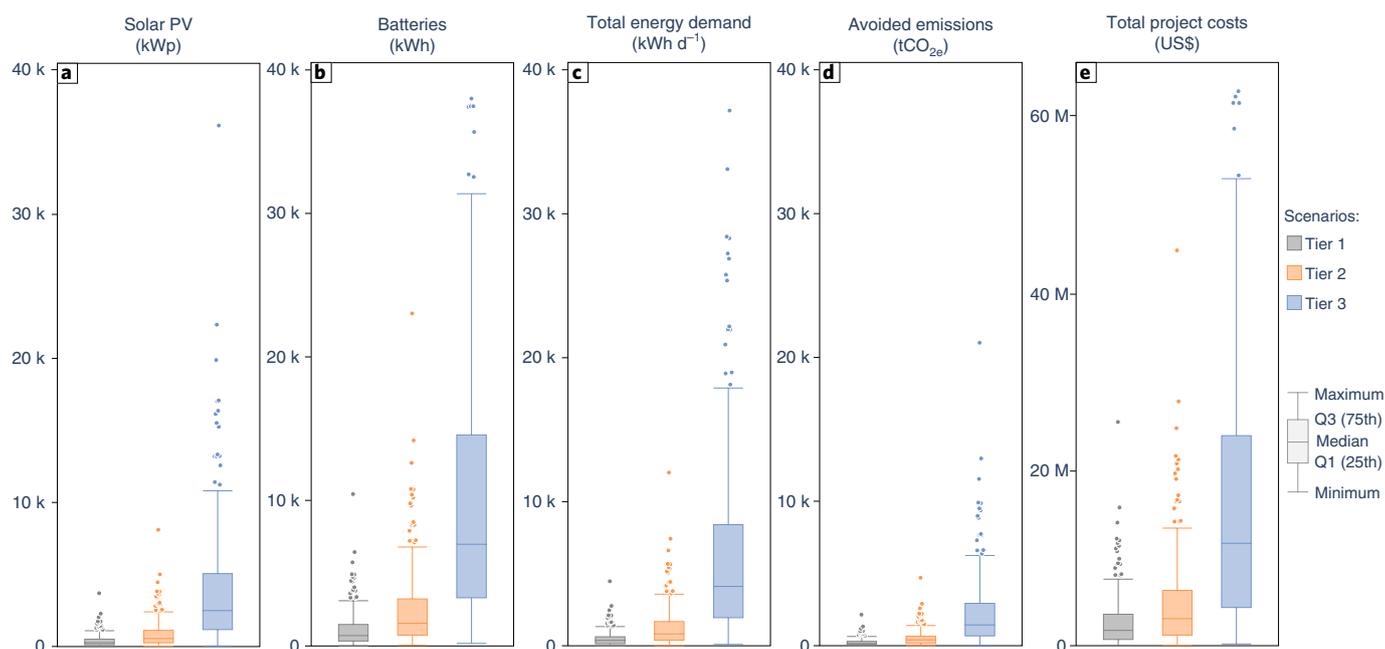


Fig. 3 | Techno-economic indicators for sustainable electricity access in refugee settlements under three electricity demand scenarios. Outliers capture the large variation in population per settlement but also the unavailability of population data per administrative unit in some locations hosting a large number of refugees. **a**, Estimated PV mini-grid capacity per settlement (solar PV). The PV sizes were optimized per settlement on the basis of the site conditions and requirements. **b**, Estimated battery capacity per settlement. The battery sizes were optimized per settlement on the basis of the site conditions and requirements. **c**, Estimated daily electricity demand per settlement. Electricity demand for residential, productive and public uses per settlement. **d**, Estimated annual avoided GHG emissions in tCO_{2e} (by using fully renewable mini-grids) per settlement. **e**, Up-front total costs (US\$ million). Up-front costs for PV mini-grid per settlement. k, thousand; M, million.

programme, wages and remittances)^{6,36}. The PV mini-grid would offer, however, a sustainable and more reliable electricity service (loss of power supply probability³⁷ at 10%), although at a higher tariff than the Rwandan national grid tariff⁵ (US\$0.22 kWh⁻¹).

Alternative electricity demand scenarios and sensitivities

To enrich the understanding of the scope of the efforts associated with providing electricity access to refugees in SSA, the RSEA DB also includes the outcomes of the same techno-economic analysis presented above, under two alternative demand scenarios. The so-called tier 1 scenario is estimated assuming an average consumption for residential loads equal to the one measured in Kalobeyei (a minimum of 0.074 kWh per household per day). The tier 3 scenario (with a minimum of 1 kWh per household per day) reflects, instead, an increase of residential electricity demand to tier 3 (ref. ³⁸) access which includes small appliances (for example, general food processing and washing machine). As visible from Fig. 3 (Supplementary Table 4), by almost doubling residential electricity demand from tier 1 to tier 2 (the number of loads remains the same) the techno-economic indicators show a twofold increase. Increasing the residential demand by five times, from tier 2 to tier 3, results in a large increment in the total up-front costs (from US\$1.3 to 5 billion). In the same way, the solar PV and battery capacity increases dramatically and this is reflected in a similar increase in avoided GHG emissions.

The fixed ratios between indicators in alternative demand scenarios derive from having common assumptions about the costs of the technical elements in the mini-grids and from the scaling of the same load profiles over all settlements. Additional field data collections would be essential to capture the variety of costs and energy needs both across refugee sites and within them and to design mini-grids that are more closely tailored to the actual situation in each settlement⁸. Other opportunities to design more specific inter-

ventions would derive from integrating the energy demand specifically associated with water services (boreholes) and, potentially, cooking needs.

Figure 4 considers, instead, the effects on LCOE values (under tier 2) of changes in economic and technical parameters. Figure 4a focuses on changes in the discount rate from the reference value of 10%. The latter is consistent with the observed practice in Kalobeyei: a foreign energy company assessing a project to be realized in a displacement setting operated under the UNHCR mandate (rather than, generically, in the hosting country) and considering all cost elements in the LCOE directly in foreign currency. Although cross-country differences in the cost of capital^{39,40} can be significant, the realization of electrification projects in refugee sites is habitually part of a concerted strategy between national and international organizations¹⁰. These strategies include measures to reduce investment risk, in the form of grants to cover up-front costs and favour projects with positive externalities (for their overall societal benefits), rather than more favourable financing conditions. All these considerations motivate the use of a single discount rate for all settlements in the RSEA DB. Nevertheless, it is important to note that even the smaller variation in Fig. 4a (from 10% to 12%; Supplementary Table 5a) corresponds to a 13% change in the median LCOE (from US\$0.30 kWh⁻¹ to US\$0.34 kWh⁻¹).

Furthermore, Fig. 4b compares, first, the LCOE values of the fully renewable systems discussed so far, with the LCOE values of an alternative technological option (also optimally sized for each settlement), that is a PV mini-grid using diesel generators as backup (current diesel cost are differentiated per country, thus include existing national diesel subsidies Supplementary Table 1b). Although the median difference is US\$0.05 kWh⁻¹, the data are significantly dispersed. Figure 4b shows also the difference in LCOE values when calculated with country-specific discount rates rather than a uniform one (Supplementary Table 5b). As expected, these

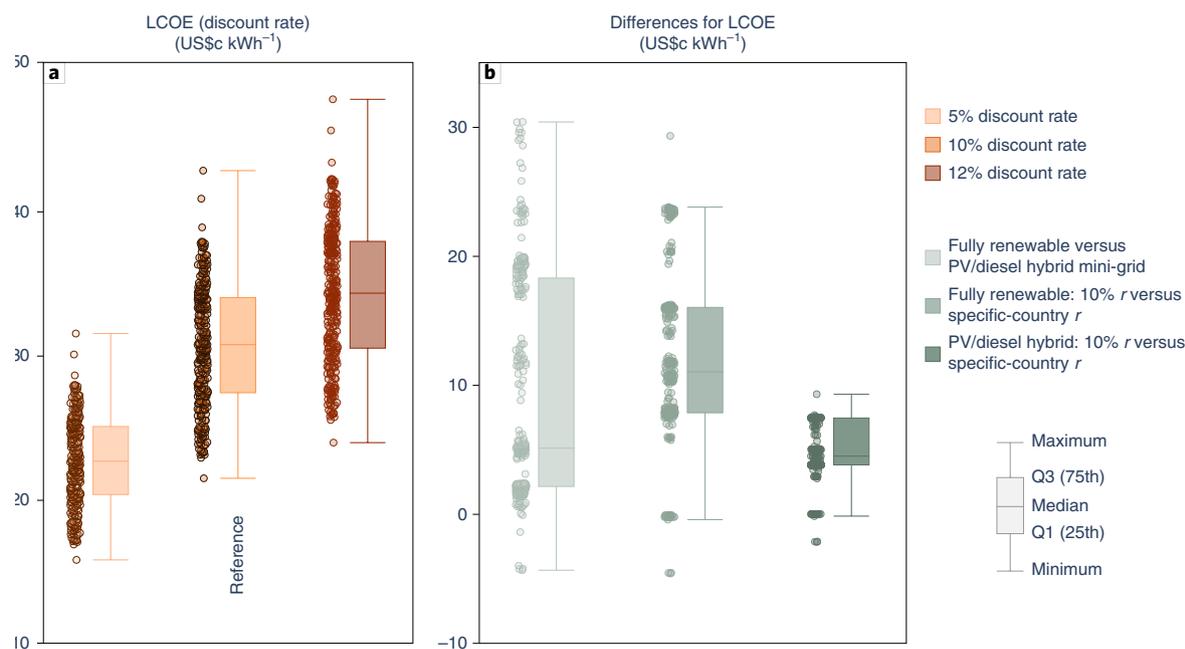


Fig. 4 | LCOE for mini-grids in refugee settlements: variation of technical and economic parameters. **a**, Discount rate (r) sensitivity analysis. LCOE values per settlement of fully renewable mini-grids (tier 2 residential demand scenario) for three different discount rates 5%, 10% (reference value) and 12%. **b**, Comparing LCOE of fully renewable mini-grids and PV/diesel hybrid mini-grids. In light green the difference between the LCOE values of fully renewables minus the LCOE values of PV/diesel hybrid mini-grids (country-specific diesel prices and discount rate of 10%). The differences in LCOE show a high degree of dispersion (spread box) and higher skewness in the upper values than lower values and also high variability outside the upper quartiles (whiskers) due to the strong influence of the country-specific diesel prices⁶². In green (fully renewable PV mini-grids) the difference between LCOE values were calculated with a uniform discount rate (10%) minus the LCOE values calculated with country-specific discount rates. In dark green (for PV/diesel hybrid mini-grids) the difference between LCOE values were calculated with a uniform discount rate (10%) minus the LCOE values calculated with country-specific discount rates and country-specific diesel prices.

differences are higher for the fully renewables systems (median value US\$0.11 kWh⁻¹) than for the hybrid ones (median value US\$0.05 kWh⁻¹) and more dispersed.

Integration with earth observations and dissemination

The data collected in the RSEA DB are suitable to support research in further directions, as well as output dissemination. To illustrate the advantage of having direct access to the RSEA DB, recall that one of the crucial aspects to consider in planning electricity access interventions in refugee settlements is the interaction with the hosting communities^{9,41,42}. Indeed, night-lights in Fig. 1 suggest that numerous refugee settlements in SSA might be located in areas where the host communities also lack access to electricity. The map in Fig. 5a analyses the matter more closely by combining the distribution of population without access to electricity¹⁸ and the boundaries of the refugee settlements (both derived from earth observations). The integration of such data can provide a first indication of where it would be sensible for electricity access projects to consider the joint needs of displaced and local populations¹².

Furthermore, Fig. 5b–f combine accessibility data^{43,44} and the geographical boundaries of the refugee settlements providing a way to capture the potential level of integration with the host community (Methods). Proximity, in terms of travel time to the refugee sites illustrates, for instance, the opportunity for the local population⁴¹ (without access to electricity) to use public services, such as health facilities, or to access businesses located in the settlement. Sharing services, not for absence of equivalent ones within the host community but, indeed, for reasons of integration, might be beneficial but, clearly, further investigation would be necessary to establish the feasibility and realism of this proposition on a case-by-case basis.

With these caveats in mind, Fig. 5e compares, for 13 illustrative cases, the cumulative population curves, capturing the number of people within a given motorized travel time to the refugee settlement. Considering that private ownership of motorized vehicles is not common in these regions, this information is mainly relevant for accessing emergency healthcare. Differences across sites are apparent. For instance, a larger number of people can more rapidly access Kyangwali in Uganda than Kakuma in Kenya, primarily due to the density of the local population (sparser in the case of Kakuma), the existing transport infrastructure and the local geographical conditions. Figure 5b–d further illustrate this concept for three sites: El Daein in Sudan, Kalobeyei in Kenya and Kouchaguine in Chad (the increase in travel time is expressed with a colour change). The maximum motorized travel time (dotted line) captures where the local population reaches the same number as the refugees in the settlement. The latter represents a theoretical upper-bound estimation of the level of integration via shared services (a maximum catchment area for the facilities). For the population without electricity within this area, Fig. 5f further illustrates the distribution of the motorized travel time per settlement. For example, the travel time to Kakuma ranges from 70 min for the nearest population to 160 min for the further population (with an average travel time of 2 h).

As for the second point, output dissemination, a selection of the RSEA data contributes to the datasets included in the interactive open-access Clean Energy Access Tool. The Clean Energy Access Tool was developed for visualizing and analysing information on electricity access in Africa and the overall energy outlook (Fig. 6). Specifically, it allows the visualization of the refugee sites, enables the analysis of the related indicators (based on user-defined polygons or at national and/or subnational levels) and the

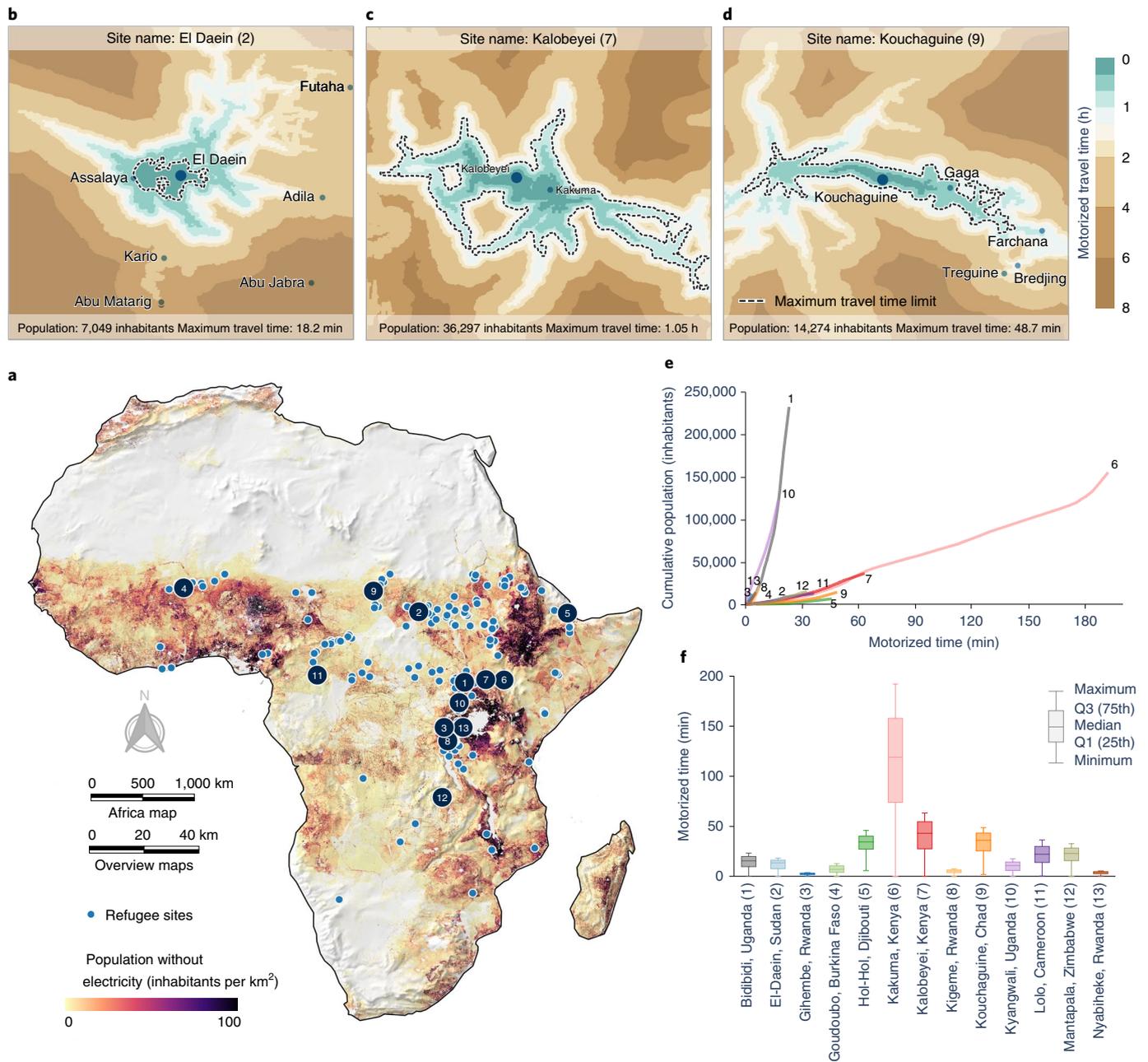


Fig. 5 | Distribution of local population without access to electricity and accessibility to refugee sites. **a**, Darker pixels represent geographical areas where the number of people per 1 km² without access to electricity is higher. **b–d**, Selected areas as indicated in **a** with accessibility as background layer, then the motorized travel time (in minutes) to the boundaries of the refugee site. The shortest travel time (<60 min) is represented in green and the longer (>2 h) in brown. The maps include the boundaries of the catchment area (dotted line) determined by the travel time needed to reach the same number of people as in the refugee sites. **e**, Cumulative population curves at given travel times to the most accessible refugee site. This highlights the pronounced differences in travel times across 13 selected refugee sites and also reflects the distribution of population within the catchment area (more or less dispersed). For instance, the travel time is much longer for site (6) than for sites (1) and (10). **f**, Distribution of motorized travel time to the refugee site. This underlines the evident differences in the distribution of travel times across 13 selected refugee sites. For instance, sites (6) and (10) have similar number of refugees; however, the travel times for site (6) show a higher degree of dispersion (spread box) and also show higher variability outside the upper and lower quartiles (whiskers). The maps were generated using the following data (collected and processed by the authors): number of refugees, location (RSEA DB), boundaries of refugee camps (OSM), shaded relief of land areas from Natural Earth (<https://www.naturalearthdata.com/downloads/50m-raster-data/50m-manual-shaded-relief/>). Population without electricity grid: ref. ¹⁸, JRC (<https://ghsl.jrc.ec.europa.eu/data.php>). Accessibility data: refs. ^{44,43}.

downloading of the datasets (RSEA DB can be downloaded from <https://data.jrc.ec.europa.eu/collection/id-0076>). Ultimately, it is expected to inform the wider public and to support institutional stakeholders’ decision-making processes.

Discussion

This work sheds light on the potential of decentralized energy systems to offer a fast, reliable and sustainable way to increase access to electricity in refugee settlements in SSA. The continental scope

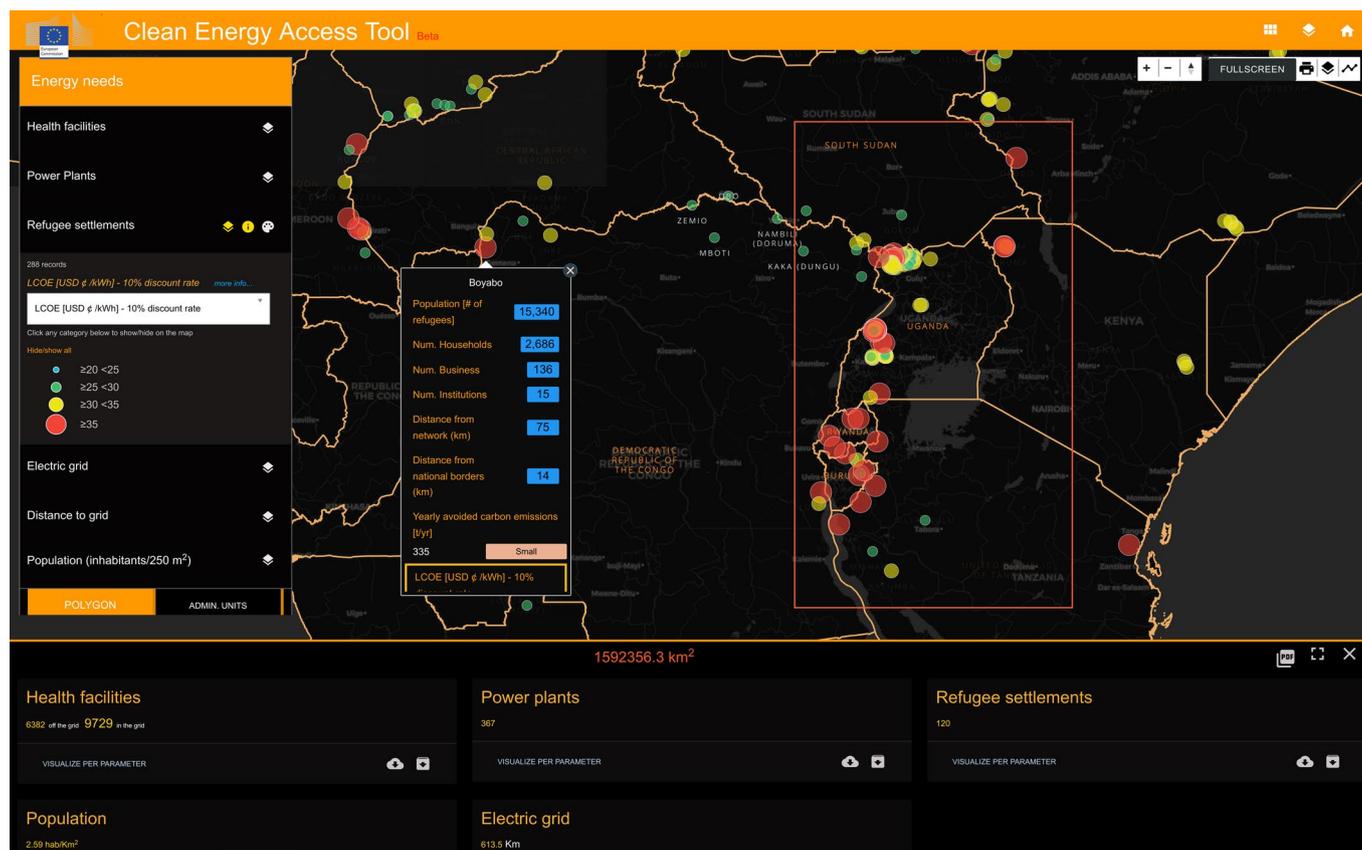


Fig. 6 | Clean Energy Access Tool, including refugee settlement analysis. Screen shot of this open-source web tool developed by the European Commission—JRC (accessible at https://africa-knowledge-platform.ec.europa.eu/energy_tool).

of the data collection and techno-economic analysis conducted in this work enable an estimation of the scale of the overall effort (US\$1.34 billion in up-front costs) and environmental benefit (0.14 MtCO_{2e} avoided per year) of providing clean electricity access in all the observed settlements. Furthermore, by facilitating access to aggregated and settlement-specific quality data, the RSEA DB and the associated web tool (https://africa-knowledge-platform.ec.europa.eu/energy_tool) can support humanitarian and development organizations in eliciting an effective response across countries and actors (for example, local government and donors) to deliver sustainable energy solutions on a large scale. Energy data in humanitarian contexts are also useful for the growing academic community studying technical solutions for evidence-based interventions. As shown, new data sources are extremely helpful to address the fragmented and incomplete nature of currently available information; and the opportunities to use the present information set to pursue other research avenues are potentially numerous as well as to tailor the information to the evolving needs and realities.

There are two important directions for future investigation. A first one regards the completeness and representativeness of the RSEA DB over space and time. The data-intensiveness of the analysis implies growing uncertainty over the reliability of the information, as some sources such as existing grid infrastructure, site boundaries and number of refugees per sites become outdated or are deemed incomplete—tracking the fast evolution of population data and energy demand is a key aspect in the humanitarian context. Also, it is important to continue to address the uncertainty regarding the quality of the collected publicly available and open-source data. Ongoing feedback from the field is the most obvious way to improve quality but also other approaches such as validation by experts, peer

review, comparison with other collected data and use of standardized and calibrated measurement for mini-grid performance.

Second, while expansions to other geographical areas using a similar approach would be useful, energy interventions in humanitarian contexts should be informed by more than only techno-economic models. Complementary methodologies include social impact assessment studies, institutional analyses, economic and ethnographic studies and community engagement processes^{42,45,46}. Particularly in protracted situations, electricity is an investment for the future. Hence, social cohesion between the settlement and the host community, current and future generations' well-being, potential impacts on the most vulnerable groups among the refugees are fundamental concerns to be addressed, together with any other competing basic needs.

Methods

Building a comprehensive database. The RSEA DB was designed and developed to gather the multidimensional factors⁴⁷ that determine the energy access dimension for refugee settlements. These factors were chiefly environmental (such as variability of solar radiation and avoided GHG emissions), technical (electrification status, distance to grid), social (population, electricity demand, social infrastructure) and economic (PV mini-grid component prices, discount factors, operation and maintenance costs). The main indicators capturing these factors are listed in Supplementary Table 6.

To retrace the steps behind the creation of the RSEA DB, note the following.

- (1) The holistic structure of the RSEA DB was informed by an extensive review of the existing literature including whitepaper reports^{1,10–14,21,32,38,48,49} and academic papers^{3–6,8,9,19,25,34–36,41,42,45,46,50,51} which focus on energy access and refugee settlements. The analysed documents were used to gather demographic figures from UNHCR statistics, to obtain field data from humanitarian contexts and other relevant data from studies on solar and hybrid (solar-diesel) mini-grids installed in refugee camps or rural communities in Africa. Studies

- on mini-grids in similar contexts were analysed in depth and technical and financial information, such as generation component prices, battery costs and discount rates were retrieved, as well as documentation on the institutions operating in the camps, number of businesses, health facilities and so on. Additional information regarding the hosting countries was also collected from literature (for example, inflation rates, currency exchange, electricity tariffs).
- (2) Field data on electricity needs were collected and retrieved from the Kalobeyei settlement in Kenya in 2020. Specifically, current electricity consumption was measured from the existing electricity supply: diesel generators, an existing PV mini-grid (metered data), solar home systems (PV and battery storage) and PV panels⁷ already owned by refugees (second-hand panels were mostly found to be in poor conditions). The data collection was conducted via a questionnaire administered to the refugee population of the settlement. The semistructured survey reached 325 interviewees, properly selected among type of end-users (households, businesses and institutions) and their geographic location inside the camp (the settlement is divided into three villages).
 - (3) The data collection was complemented by stakeholder interviews. The surveyed experts were selected from various humanitarian organizations (Danish Refugee Council, Norwegian Refugee Council and UNHCR), development actors (Deutsche Gesellschaft für Internationale Zusammenarbeit, Global Plan of Action, Netherlands Development Organisation and United Nations Institute for Training and Research), research institutions (École Polytechnique Fédérale de Lausanne and Imperial College London) and civil society organizations (Renewia Energy Kenya Limited) involved in the coordination and organization of refugee settlements in SSA. A complete list of the stakeholders interviewed is stored in Supplementary Table 7 (the response rate was around 10%). Selection of the questions used for the interviews was mainly based on the background, expertise and agency-provenience of the interviewees. Qualitative discussions with the experts were aimed to cross-check and validate the information from the literature, understand the socio-economic framework in refugee settlements in Africa (for example, electrification conditions, social context and refugee energy routines), to obtain verifiable data sources inherent to energy-related humanitarian operations and to complete the technical data input for actual energy operations based on field data from the settlements (system losses, efficiency, lifetime of the system and so on).

After completing the data collection and the techno-economic analysis described below, the following parameters were integrated in the RSEA DB for each of the settlements.

- (1) Descriptive parameters: name and coordinates of the site location, name and type of the refugee settlement, number of refugee population, actual or estimated number of households, businesses and public institutions. Additional parameters are distance to the national electric grid and the closest national border.
- (2) Energy demand parameters: residential, business and institutional daily electricity demand at settlement level (kWh d^{-1}), estimated at year 5 of the lifetime of the project (20 yr). Daily electricity demand estimated at year 0 for a single household, business and public institution ($\text{kWh per connection per day}$).
- (3) Techno-economic parameters: optimized PV and battery size. Up-front cost of generation (PV, battery and balance of system). Up-front cost of distribution (customer connection fee, overhead lines and substation). Soft cost for logistics and project management and for contingencies. Replacement cost (inverter and battery). LCOE values with three discount rates (5%, 10% and 12%). LCOE sensitivity analyses for operation and maintenance costs (2% and 3% of up-front costs) and four levels of grant coverage of the customer connection fee (25%, 50%, 75% and 100%).
- (4) Climate parameters: daily and yearly avoided GHG emissions at year 5 of the lifetime of the project.
- (5) Geospatial datasets: PVGIS¹⁵, GHSL¹⁷, NOAA⁵², OSM⁵³ and national grid⁵⁴ were integrated in the RSEA DB to geographically contextualize the refugee settlements (distribution of population, solar radiation, accessibility maps, existence of electricity grid and night-light imagery).

The RSEA DB tracks 288 settlements organized in 203 refugee sites. The settlement coincides, in most cases, with the site. However, for some sites hosting a large number of refugees, population data were publicly available for smaller administrative units (for example, Bidibidi in Uganda, is organized in five units or 'zones' and Kakuma, in Kenya, in four 'villages'). Hence, each subadministrative unit within the same site was traced as a different settlement. Conversely, in the absence of information regarding the subadministrative units, some large refugee sites had to be considered as a single settlement (for example, Nyarugusu in Tanzania).

Estimating electricity demand and daily load profiles. The electricity demand and load profile per refugee settlement were calculated by considering the three types of users below.

- (1) Residential users: the electricity demand at the household level corresponds to a small-scale power of needs (for example, for tier 1, task light and

- phone charging; and, for tier 2, adding general lighting, television, fan or computing).
- (2) Productive/ business users: the electricity demand for income-generating activities includes energy requirements for commercial usage and industrial light (small businesses).
- (3) Public/ institutional users: this category consists of demand for facilities such as street lighting, back-office administration, communication services, health-care and education services.

Note that only users located inside the settlement were considered. For instance, humanitarian compounds located outside the camps are not included. The number of household users in each settlement was retrieved from UNHCR statistics or estimated from the average number of people per household of each country. The number of businesses and institutions were retrieved from the literature or expert interviews (nine settlements only) or estimated using a fixed ratio of business and institutional users to residential ones (respectively, 0.0507 and 0.0059, computed as average values across the nine observed settlements)—in fact, the number of businesses and institutions will vary (perhaps significantly) across settlements.

Settlement-specific daily load profiles for households, businesses and institutions were derived from the corresponding daily load profiles estimated for Kalobeyei. The latter process involved assessing, during the field visit, the hourly electricity demand of the respondents having access to any source of electricity in each village and adjusting these figures to the actual number of users. The available sources of electricity were an operational mini-grid (7% of the respondents), several diesel generators (9%) and solar lamps or second-hand PV solar panels purchased from the market (45%)—the remaining 61% of the respondents had no access to electricity. The estimated daily load profiles per type of user and per village in Kalobeyei are shown in Supplementary Table 8b.

To calculate, for each user type, a settlement-specific daily load profile, five corrective factors (CFs) were defined and applied to the load profiles in Supplementary Table 8b. These factors adjust the load profiles estimated for Kalobeyei, to the characteristics of each settlement and account for: the number of connections per type of user (CF1); the presence of users opting to remain with a pre-existing electricity provider (CF2); the fact that part of the users in Kalobeyei were already connected to a mini-grid (CF3); and the different tiers (CF4 and CF5 for, respectively, tier 2 and tier 3). A full description of the CFs can be found in Supplementary Table 8a. The aggregated daily load profile for each settlement is the sum, over all user types, of the settlement-specific daily load profiles per type of user—for an example see Supplementary Fig. 1.

Note that for the purpose of sizing the mini-grid capacity, the hourly power demand which composes the settlement-specific daily load profile per user type, is assumed to grow annually by 10%, starting from the initial values estimated for year 0 with the CFs and until year 5. After year 5, the hourly power demand remains constant for the lifetime of the project. These choices mimic the assumptions on potential demand growth made by mini-grid developers in Kenya. Expert interviews confirmed that the limited available experience and the uncertainty regarding the number of refugees living in each settlement can strongly affect the reliability of long-term forecasting for these projects.

The aggregate settlement-specific electricity demand and the settlement-specific electricity demand per user type, were calculated from the load profiles. Hence, the daily electricity demand for a single household depends on the year and on the scenario:

- (1) Tier 1—this scenario was based on the data registered in Kalobeyei (0.07 kWh d^{-1} per household in year 0).
- (2) Tier 2—this scenario is coherent with the SDG 7 framework^{20,24} and with the goal set by UNHCR^{21,51} for refugee settlements (0.20 kWh d^{-1} per household in year 0).
- (3) Tier 3—this scenario captures a potential increase from the current goal (tier 2) to the equivalent of tier 3 (ref. ³⁸) access (1 kWh d^{-1} per household in year 0).

The daily electricity demand for a single business and for a single institution depend only on the year and were also derived from the field data collected in Kalobeyei (0.26 kWh d^{-1} and 3.14 kWh d^{-1} , respectively, in year 0).

Optimizing the PV and hybrid PV/diesel mini-grid. The total amount of solar irradiation and the intermittency of the solar irradiation depend strongly on the geographical location. On the basis of these data and the specific load characteristics of each refugee settlement, the PV mini-grid was sized with 100% renewable energy and with PV plus diesel generator as backup. The optimal size of the PV array and battery storage for a given settlement was computed to ensure loss of power supply probability⁵⁷ at 10%.

The annual electricity generated yearly by the PV mini-grid was calculated for each settlement using a combination of models²⁰: (1) a model for effective irradiance with hourly solar radiation measured from satellites (combined with temperature and wind speed data from re-analysis); (2) a PV output power model with measured data on module performance; and (3) a model for battery performance based on measured battery data. This methodology has been described in detail and validated^{19,20,55}. As for the hybrid system^{36,57}, current diesel

cost were used, differentiated per country, thus they include national diesel subsidies.

The distribution network consists of low-voltage overhead feeders sustained by poles and end-user connections. Settlements with a number of households above 2,000 (60% of the observed ones) include a substation as an additional distribution element.

Assessing electrification costs. The cost of providing electricity to each settlement via a PV plus battery storage mini-grid was analysed in two ways: (1) estimating an up-front capacity cost on the basis of the system specifications; and (2) computing the corresponding LCOE. The up-front capacity cost was calculated on the basis of the PV plus battery storage mini-grid optimization outputs (PV size and battery size) and three main cost categories: generation, distribution and soft costs. Field data collected in Kenya were used to set these three cost categories⁷ (Supplementary Table 1).

For each refugee settlement (n), the LCOE was calculated using a 20 years lifetime (T) and a discount rate (r) of 10% (refs. ^{15,58}). The up-front capacity costs (Up_cost_0 in year $t=0$), the annual operation and maintenance cost (O&M_{*t*}), the asset replacement (R_t , battery and PV inverter at year 10) and financial costs (F_t) were taken into consideration by the following equation:

$$LCOE_n = \frac{Up_cost_0 + \sum_{t=1}^T \{(O\&M_t + R_t + F_t) / (1 + r_n)^t\}}{\sum_{t=1}^T \{(ES_n) / (1 + r_n)^t\}} \quad (1)$$

where O&M_{*t*} costs are 1% of the up-front capacity costs, financial expenditures include VAT payments, insurance, interest expenses and ES_{*n*} is the annual electricity production from the PV mini-grid. The same financing structure used in Kalobeyei was assumed, with 90% grant, 8% equity and 2% debt.

The indicator LCOE_{*n*} includes the entire up-front capacity costs. The indicator LCOE_{*gen*} (also reported in the database) is the part of the LCOE for the generation components only. The reference values and variations of the parameters used in the sensitivity analyses (discount rate, O&M costs and customer connection fee) are shown in Supplementary Table 5a. Supplementary Fig. 2 illustrates (for the reference tier 2 demand scenario) that, starting from O&M costs equal to 1% of the up-front costs⁵⁹, an increase to 2% and 3% corresponds to a LCOE increases of 1.5% and 1.7%, respectively. In a similar manner, assuming that the customer connection fee might be covered partially (25%) or entirely (100%) by a grant also lead to relatively small decrease in the median value of the LCOE (comprising between -0.1% and -1.3%).

The effects on the LCOE values (under tier 2) of varying the discount rate were illustrated in Fig. 4a. To study the effect of a country-specific discount rate on the LCOE (Fig. 4b), weighted average capital cost values were calculated⁴⁷ with recent input data on equity rate of return and debt interest rate in each country (World Bank/IMF lending interest rate, 2021)⁶⁰ using the methodology described previously⁴⁰. The country-specific weighted average capital cost values (Supplementary Table 5b) were then included in the LCOE location-specific estimates for both the fully renewable and the hybrid PV/ diesel mini-grids^{46,57}.

Estimating avoided emissions. The estimation of the carbon mitigation potential of using fully renewable mini-grids is based on the avoided GHG emissions in CO_{2e} (ref. ⁵⁹). The avoided GHG emissions were calculated by computing the annual emissions of a stand-alone diesel generator supplying the settlements' electricity demand in year 5, when demand becomes stable and the system is operating at full capacity. Supplementary Table 9 summarizes the relevant parameters and sources used to compute the emission factor (0.93 tCO₂/MWh⁻¹).

Observing the host communities. The lack of harmonized geodata concerning the African population, together with inconsistent demographic information produced through census campaigns, has prompted the scientific community to extract information from the available satellite remote sensing archives⁶¹. Consistently, a multicriteria site-selection algorithm was designed to identify the populated areas at a given motorized travelling distance from 13 selected refugee settlements and without access to electricity. The criteria used to delineate these areas are:

- (1) Identify the borders of the selected refugee settlements by combining cartographical (OSM) and earth observation data. Missing boundaries were added through visual interpretation of satellite images (Microsoft Bing aerial images).
- (2) Estimate the cumulative travel distance by motorized⁴⁴ means for the selected refugee settlements. The calculation considers the travel distance starting from the settlement borders until reaching the maximum distance of 10 km. The areas inside each site were not considered in this analysis.
- (3) Extract the catchment area considering the population without access to electricity¹⁸ around the refugee settlements that corresponds to the total population living inside these settlements.

The requirement of data extraction for obtaining missing settlement boundaries limited the analysis to a few settlement areas. This limitation can be overcome in future analyses if cartographic information becomes available or a

specific algorithm is developed to automate the process of settlement boundary delimitation and eliminate the need for visual interpretation techniques.

Data availability

The RSEA DB generated during this study is available in two file formats (csv and geopackage) at <https://data.jrc.ec.europa.eu/dataset/4261bf3c-7e8e-4b16-925b-68cfd4eade37>. Visualization interactive Clean Energy Access Tool is available at https://africa-knowledge-platform.ec.europa.eu/energy_tool. Source data are provided with this paper.

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Author contributions

D.B., M.M.G. and E.F. conceived and designed the experiments. D.B. performed the experiments. D.B., M.M.G., E.F. and F.F. analysed the data. D.B., M.M.G., E.F. and F.F. contributed materials/analysis tools. D.B., M.M.G. and E.F. wrote the paper.

Competing interests

The authors declare no competing interests.

Ethics approval and consent to participate

According to standard procedures for energy assessment surveys in refugee settlements, the UNHCR office in Kakuma, first, and the Refugee Settlement Committee in Kalobeyei, second, were asked for and granted permission to conduct the survey. A member of the Committee accompanied the interviewers for the entire survey duration. Each of the individual respondents granted informed consent. Respondents were selected on a geographical basis to include all three administrative units that compose the settlement and the various countries of origin of the refugees (different areas of the settlement host different nationalities). Out of 325 in-person interviews, 234 were conducted with households, 68 with small businesses and 23 with institutions. The survey questions are available in the Supplementary Information.

Additional information

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1038/s41560-022-01006-9>.

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