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Attention to detail: exploring effects of model resolution and complexity in geospatial electrification modelling

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Abstract
In 2021, 675 million people globally lack access to electricity. Geospatial electrification tools can be used to identify the mix of grid-extension, mini-grids and stand-alone technologies that can supply currently unelectrified areas at the lowest cost. Several such tools have been developed, at different levels of modelling detail and complexity. In this paper, we improve the Open Source Spatial Electrification Tool (OnSSET) to develop a flexible geospatial electrification tool that can still run lighter rapid assessments for a first estimate of the technology split, but now also more detailed analysis with higher spatial and temporal resolution used for grid routing, distribution network design and optimization of hybrid mini-grid generation introduced through new algorithms. We compare the existing light and new more detailed versions of the tool through a case study of the north-western parts of the Democratic Republic of the Congo. We find that the new grid routing algorithm led to more off-grid technologies, and that the detailed design of distribution networks leads to a reduction in stand-alone technologies. The detailed optimization of hybrid mini-grids displays varying effects at different demand levels. Given the increased computational effort that is observed with higher modelling detail, we discuss the implications for scenario design and selection of geospatial electrification tool for future analyses aiming to support the achievement of SDG 7.

Keywords Energy planning, Electricity demand scenarios, On-grid and off-grid technologies, OnSSET, SDG7

1 Introduction

Energy system models can be used to understand energy systems and support policy- and decision-making. There are numerous energy system models developed to represent different energy systems and to answer different questions. The energy system captured by these models can vary from a single process e.g. within a power plant, to a specific energy sector to the whole national or continental energy system including a multitude of fuels, sectors and interlinked processes [1]. Energy system models can be used to predict developments with regards to demand and/or supply, investigate how changing some part or input of the system affects the system as a whole or to examine how to achieve a specific outcome [2]. As with any model, energy system models represent simplified versions of reality, most commonly implemented through a set of mathematical equations. The theoretical structure, implementation method and level of detail of the model depends on the system to be examined and the question(s) to be answered [2]. More detailed and complex models may be developed to improve the model performance, reduce structural uncertainty and provide greater insights. At the same time, there are key trade-offs, for instance increased complexity may reduce transparency and repeatability, increase data collection and management requirements, and require higher computational requirements and associated costs [3].

The field of electricity access provision in developing countries has seen a steep increase in the use of energy system models since the turn of the century. To increase access to electricity in an efficient and cost-effective manner, a combination of centralized grid and off-grid (mini-grid and standalone) technologies can be used. Integrated energy planning efforts consider these technologies in conjunction; some settlements may be electrified by extending the centralized grid to connect to those areas, some by deploying mini-grids and others by stand-alone technologies such as Solar Home Systems (SHS) [4]. Here, a particular type of energy system model referred to as *geospatial electrification models* can be used to understand which of these technologies to be used and where. These models are often used towards the achievement of Sustainable Development Goal 7, which is to *ensure access to affordable, reliable, sustainable and modern energy for all* by 2030 [5]. Access to modern energy, and electricity in particular, is a key enabler of socio-economic development, and is interlinked with the achievement of all of the SDGs, and ~ 85% of their targets [6]. Still, the latest Tracking SDG7 report estimates that 675 million people remained without access to electricity in 2021 [7]. In fact, the COVID-19 pandemic has slowed down progress in many countries, and made electricity unaffordable to an estimated 30 million people that had access prior to the pandemic [8]. At current trends and policies, 670 million people could remain unelectrified by 2030 [9].

Geospatial electrification models in this paper refer to models that seek to identify the least-cost technology for each settlement in a country or region. To do so, they draw on geospatial data to understand the characteristics of each settlement, which is used to identify the least-cost electricity supply technology of each settlement. These geospatial data include e.g. the distance from a settlement to the existing grid infrastructure, the electricity demand of the settlement and the energy resource availability at the location of interest [10]. There are optimization tools developed to analyze the energy system for a single settlement in order to find the best technology to meet the demand of that settlement, drawing on detailed information about energy resource availability, load curves and the components of the energy systems. Perhaps the most common of these tools in the literature is HOMER, which is used for detailed micro-grid sizing [11]. However, geospatial electrification models identify the least-cost technology for a multitude of settlements (which can range from thousands up to millions depending on the scope of the analysis) to understand how electricity access can be scaled up effectively on national or regional scales. Given the scale of this problem, these geospatial electrification tools generally use less detail for the modelling of each settlement compared to models analyzing only a single settlement.

The level of detail and model complexity varies largely between different geospatial electrification tools. Such variations depend on the purpose for which the different tools were developed as well as the data available at that time. Furthermore, many of these tools have evolved over time. Ciller and Lumbreras [11] reviewed existing geospatial electrification tools used for electrification planning. They provided a comprehensive formulation of the rural electrification planning problem and proceeded to define three classes of geospatial electrification tools: *pre-feasibility tools*, *intermediate analysis tools* and *detailed generation and network design tools*. Pre-feasibility tools are the least detailed of these tools, providing first-pass estimations on the least-cost electrification option for settlements or grid cells. Intermediate analysis tools provide an additional level of detail and complexity, performing better with regards to network layouts and/or generation sizing. Finally, detailed generation and network design tools provide accurate designs of generation, transmission and distribution networks including electrical constraints for all settlements. These are the most detailed and complex of the three classes. While the pre-feasibility tools are the most simplified and therefore provide the least detailed results, the other two categories require an increasing amount of data and computational effort. Most of the tools developed to date belong in the pre-feasibility or intermediate analysis class, with only one, the Reference Energy Model, meeting the requirements of detailed generation and network design according to Ciller and Lumbreras [11].

All three classes of geospatial electrification tools have been used in literature, publications and platforms by international organizations and for national electrification planning. Ciller and Lumbreras place the Open Source Spatial Electrification Tool (OnSSET) in the pre-feasibility class [11]. OnSSET has been used in scientific publications (e.g [12–14]), for analysis in the International Energy Agency's World Energy Outlook [15–17], the Global Electrification Platform [18], and in country applications in (e.g. Somalia [19], Madagascar [20] and Benin [21]). Other examples of this class include InitGIS, which has been applied in Ghana [22], and methodologies by the JRC applied in e.g. Burkina Faso [23] and Kenya [24]. Similarly, in the intermediate analysis class the Network Planner tool is found both in the scientific literature applied to e.g. Ghana [25] and Kenya [26], and for national electrification planning in Liberia [27] and Senegal [28]. In the same class of tools, GEOSIM has been applied in several countries including Benin, Burkina Faso, Cameroon, Ethiopia, Madagascar and others [29]. In the detailed generation and network design tools class, the Reference Energy Model (REM) has been applied in e.g. India [30], Kenya [31], Rwanda [32] and Uganda [33].

The examples in the previous paragraph represent only a subset of studies and applications using geospatial electrification models. Still, it is evident that there is a substantial overlap in the countries where these models have been applied. Morrissey [34] set out to compare the results from published geospatial electrification models. Given that studies target different countries or regions, include different technologies and consider different scenarios (e.g. with regards to demand levels and costs) they found limited scope for comparison. However, even in cases where two models examined the same area and similar demand levels, the least-cost split between the electricity supply technology types varied largely. This can be attributed to differences in input data, demand estimations and scenarios, as well as differences in the computational tools themselves [34]. Lack of data in particular is an issue often referred to in the literature and reports on geospatial electrification modelling. In some cases the data does not exist at all, is partly available or is outdated. In others it is not openly available and could not be used by the analysts [13, 34, 35]. This lack of data could limit the choice of tool and modelling detail.

The objective of this paper is to examine how differences in modelling detail and complexity affect the geospatial electrification models in terms of identified electricity supply technology mix and computational requirement. We develop new methodologies for more detailed modelling of distribution networks, routing for new grid extension and hybrid mini-grid generation optimization. We integrate these into the existing OnSSET tool, allowing it to be used at different levels of detail. With these improvements, the OnSSET tool is able to perform all of the functions of the *intermediate analysis* tool, although still not including the load-flow analysis and electrical constraints required for *detailed generation and network design tools.* Doing so, we create the first flexible geospatial electrification tool that can be used both for rapid pre-feasibility analysis and for more detailed intermediate analysis. The improved OnSSET tool is tested on a case study on the north-western parts of the Democratic Republic of the Congo (DRC) using different levels of modelling detail. The rest of the paper is structured as follows; the *Methodology* section presents OnSSET and the new developments to incorporate further modelling details, the *Study area and model setup* section provides background information about electricity access in north-western DRC and outlines the model developed, the *Results and discussion* section presents and discusses the results of scenarios with different levels of modelling detail and complexity, and finally the Conclusions section presents the main findings of this paper and recommendations for future work.

2 Methodology

Electrification pathways for the northwestern part of the DRC are explored using OnSSET [12]. The tool is modified in this paper to be able to work at different levels of detail with regard to transmission and distribution network calculations, and mini-grid sizing. The rest of this section presents a general overview of OnSSET, followed by more detailed descriptions of the distribution network, transmission network and mini-grid sizing modules that are modelled using different levels of detail and complexity.

2.1 Overview of the Open Source Spatial Electrification Tool

OnSSET is a least-cost geospatial electrification tool. The tool compares stand-alone technologies (while the tool can consider both diesel and SHS for stand-alone technologies, in this study only SHS have been included), mini-grids and extension of the centralized grid network for each settlement in the study area. The technology that can meet the demand at the lowest Levelized Cost of Electricity (LCOE) is selected in each settlement. The LCOE takes into account all of the costs (investment, operation and maintenance) divided by the electricity demand met over the life-time of the project, with both costs and electricity demand discounted to the start year of the analysis. The LCOE can be used to compare technologies with different cost structures [36], e.g. technologies with high up-front investment costs with technologies with lower investment costs but higher running costs. Note that this comparison is made from a technical standpoint to minimize overall system costs, and does not take into account e.g. profit margins or subsidies, which depend on how the electricity supply technologies would be financed.

The general workflow in OnSSET can be divided into seven steps described below, and summarized in Fig. 1:

1. *Creation of settlement clusters.* First, the population settlements that act as the basis of the analysis are generated. These clusters delineate each settlement in the area, and can be created from high-resolution raster data of population counts (see [37] for more details), or from building footprints, as further elaborated below.
2. *Collection and extraction of geospatial information.* First, geospatial information is collected and extracted to each settlement. This includes at a minimum the settlement area and population, energy resource availability, distance to existing electricity infrastructure (which may include HV lines/MV lines/substations/distribution transformers and mini-grid locations, depending on data availability), land cover, elevation and night-time lights. This may further be complemented by other geospatial datasets, such as locations of health and educational facilities, agricultural electricity demand, GDP or wealth indicators, depending on the scope of the study.
3. *Identification of electrified settlements.* Next, the settlements that are already electrified at the start year of the analysis are identified. Here, GIS data on existing energy infrastructure is combined with night-time lights and electricity access statistics. Settlements that are close to the existing power infrastructure, and where there is light that is visible during the night-time, are considered to be already electrified. The model also takes into account that settlements can be partially electrified, drawing on the night-lights data to identify how much of the population resides in areas where there is light at night. Further elaboration on the calibration and the effects of using different power infrastructure elements for the calibration is found in [13].
4. *Population projection and demand assessment.* Population is projected to the target year(s) of the analysis, based on expected growth rates. Furthermore, the demand is estimated in each settlement for the demand sectors included in the analysis. This demand can represent either an estimate of the current or future demand in a settlement, or a target level of electricity services to be enabled. Previous applications have used exploratory analysis studying the least-cost options where all of the population is assigned in turn each of the five Tiers of the Multi-Tier Framework (MTF) [12], different Tiers for urban and rural settlements (e.g [38]). , individual

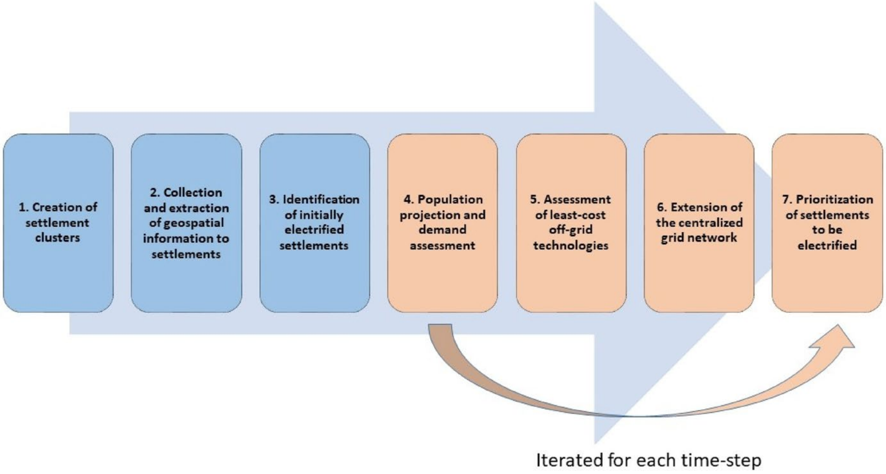

Fig. 1 Steps of a geospatial electrification analysis using OnSSET

assessments for the settlements based on poverty and GDP indicators (e.g [13]). or demand estimates based on stakeholder elicitation interviews combined with econometric projections (e.g [39]). Additionally, health, education, and agricultural demand has been included based on where these activities are located.

5. *Comparison of off-grid technologies.* In the next step, the LCOE of each of the off-grid technologies are calculated. For stand-alone technologies, each household and other demand node has their own electricity supply system. For mini-grids, there is a common generation system for the whole settlement, as well as a distribution network connecting all demand nodes. Finally, the LCOEs are compared for all of the off-grid technologies, and the least-cost off-grid supply option is selected.
6. *Extension of the centralized grid network.* In the fifth step of the analysis, the model identifies where grid-extension can provide electricity at a lower cost than the least-cost off-grid supply options. The cost of the centralized grid includes the line(s) required to connect to the settlement, the distribution network within the settlement and the cost of electricity generation by the power-plants connected to the centralized grid network.
7. *Prioritization and time-steps.* OnSSET includes a time-step functionality to work with multiple time-horizons, and a target electricity access rate by the end of each time-step [13]. This means in each time-step, the model selects which settlements to be electrified to reach the target electrification rate, according to the prioritization scheme selected by the user. This serves a starting-point for the next time-step, which takes the identified technology roll-out as a starting point for the continued analysis.

The first version of OnSSET (2017) [12] would be classified as a *first pass* tool suited for pre-feasibility studies according to the aforementioned classification introduced by Ciller and Lumbreras. This version of OnSSET divided the study area into raster grid cells, generally 1 km^2 or larger, and compared the least-cost electricity supply technology by calculating the LCOE based on annual energy resource availability and demand using the analytical expressions introduced in [36]. The transmission and distribution network length in each cell was calculated based on an assumption of symmetrical distribution of the population throughout the square-shaped grid cell, a clustering factor representing whether settlements are uniformly dispersed in the cells or clustered and constraints on the maximum capacity and length of the MV and LV lines, following the methodology presented in [40].

In 2019, OnSSET was modified to work with vector-format settlements in [13]. That is, each settlement is represented as a single polygon of varying sizes, rather than a square grid cell of uniform size (see Fig. 2). The transmission and distribution network calculations were modified accordingly, extending from settlement to settlement rather than through adjacent grid cells. In this paper, we refer to the updated version of OnSSET from 2019 as the *light version*. The new version presented in this paper including the new algorithms for distribution network sizing, transmission network routing and mini-grid sizing described below is referred to as the *detailed version* in this paper. Note that the naming here is used to distinguish between the versions compared in this paper, and that both light and detailed are relative concepts. E.g. the version presented by Korkovelos et al. [13] (*light* version) provided an improvement in modelling detail compared to the version presented by Mentis et al. [12].

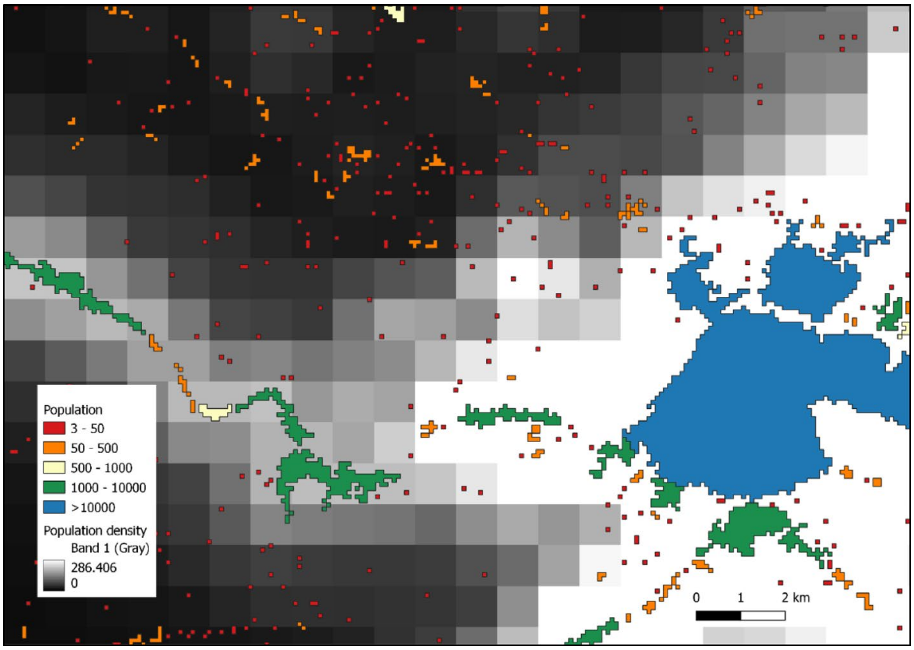

Fig. 2 1 square kilometer population raster layer in gray-scale (from WorldPop [41]) vs. clusters (in colour) based on high-resolution raster data created by [37]. Each polygon made from contiguous high-resolution raster cells represents a unique cluster. Notably, the clusters may be both smaller or larger than the raster data, which will eventually affect the choice of least-cost technology in a geospatial electrification model

A clustering tool was developed by Khavari et al. to cluster high-resolution[1] population raster cells into settlement polygons based on the distance between cells [37], which can be used in the light version of OnSSET. Figure 2 displays the clusters developed by Khavari et al., overlaid on 1 km^2 raster data from WorldPop [41]. The population within each of the larger raster cells may be split between several settlements polygons, whereas some settlements polygons instead span several of the larger raster cells.

A subsequent study by Khavari et al. [26] compared the effect of running OnSSET using raster layers and running it with vector polygons developed from high-resolution raster data using different clustering methodologies. They found that running the geospatial electrification analysis using raster layers more often led to higher costs and higher shares of off-grid technologies as the least-cost electrification option. The study also concluded that the aggregation method for cluster creation is one of the key factors for the final technology split and total investment cost, and that sensitivity analysis on the clustering parameters should be undertaken for robust electrification results [26].

In this paper, we further improve the clustering process by using more granular data, using building locations rather than high-resolution raster population data to create the settlement clusters. The Open Buildings dataset is used as the basis for the clustering process. This dataset is openly available, with buildings detected from satellite imagery for countries in Africa, South Asia and South-East Asia [43]. The buildings are clustered using the Density-Based Spatial Clustering of Applications with Noise (DBSCAN) algorithm [44], similar to the method followed by Khavari et al. [41]. The DBSCAN algorithm is flexible with regards to the size of the clusters, can filter out noise, and does not

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[1] 100 m x 100 m rasters were used to create settlement polygons for all countries in sub-Saharan Africa.

require the user to specify the number of clusters beforehand. A maximum distance of 200 m[2] between points to be considered as the same cluster is applied. Furthermore, the alpha shape [45] of each cluster is identified to identify the boundaries and area of the clusters. Figure 3 displays a selection of buildings and the resulting clusters following this methodology.

2.2 Distribution network

The sizing of the distribution network in the light version of OnSSET is presented in Korkovelos et al. [13]. These distribution network calculations are based on the area of the settlement and the number of demand nodes in the settlement. As these calculations were developed for clusters developed from high-resolution raster data, they do not consider more granular information on the shape of the settlement or how the demand nodes are distributed within the settlement. Instead, the algorithm assumes that settlements are circular and that the demand nodes are evenly distributed throughout the settlement. In the present study, a new algorithm with improved detail is developed based on the actual building locations within the settlement. Below follows a description of the approach by Korkovelos et al., and the new algorithm based on building footprints.

2.2.1 Light distribution network calculations

The distribution network calculations in the light version of OnSSET are based on the algorithm presented by Korkovelos et al. [13], which require only the settlement area and number of demand nodes (households and any additional facilities to be electrified) as geospatially derived inputs. The algorithm makes use of geometrical considerations

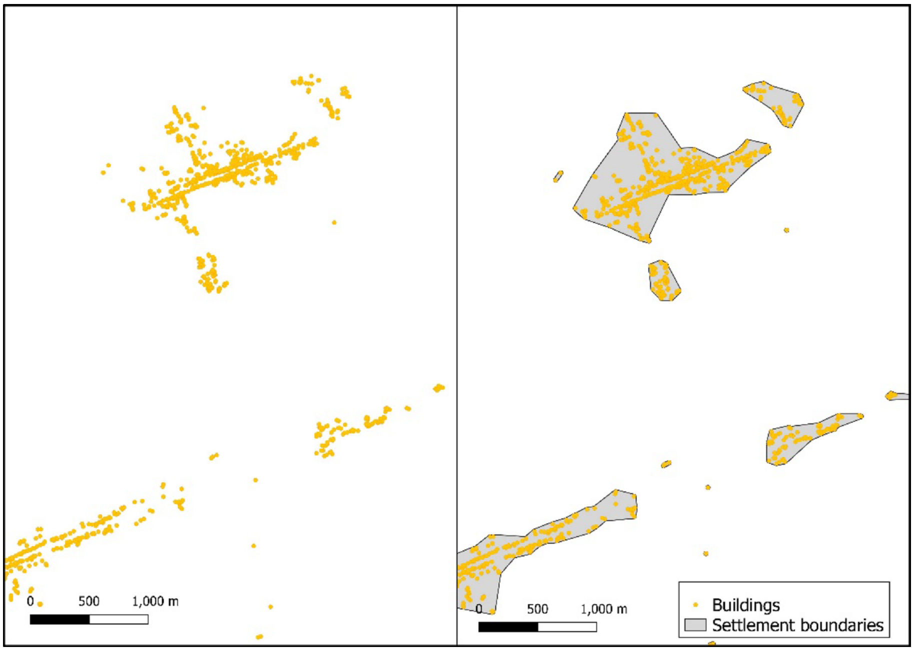

Fig. 3 Updated clustering algorithm based on building data. On the left are the individual building footprints, and on the right are the clustered buildings and the alpha shape cluster geometries

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[2] A comparison of different maximum distances by Khavari et al. [42] showed that the 200 m distance led to the lowest electrification investment costs in two out of three countries examined. Distances above 400 m led to the highest costs in all three countries.

and constraints on the maximum capacity and length of Medium-Voltage (MV) and Low-Voltage (LV) lines as well as distribution transformers to estimate the number of transformers and length required of each of the line types required for the distribution network. To do so, the following steps are undertaken:

1. The number of distribution transformers are determined. The number of distribution transformers are calculated to ensure that (i) the load supplied by a distribution transformer does not exceed the maximum power capacity of the transformer, (ii) the transformer does not supply more than a maximum number of demand nodes (the default number is 300) and (iii) the distribution transformer can only supply the area of a circle with a radius equal to the maximum techno-economic length of LV lines (default is 500 m).
2. In the second step, the lines connecting the distribution transformers and a distribution substation, placed in the center of the settlement, are calculated, assuming the distribution transformers are evenly distributed within the settlement.
3. Finally, the length of LV lines connecting the demand nodes to the distribution transformers is calculated, assuming demand nodes are evenly distributed both between distribution transformers and within the circle of distribution transformers. An example of the distribution network using these assumptions is seen in Fig. 4.

2.2.2 *Detailed distribution network calculations*

The detailed distribution network design is based on the same constraints as the distribution network design in the light version of OnSSET. However, this algorithm is based on the actual location of buildings within the settlements, resulting in a more realistic network design for each settlement. To do so, the following steps are undertaken (visualized in Fig. 5):

1. First, the LV poles from which the demand nodes are connected by a service drop are identified. Two constraints are imposed; (i) the service drop cannot exceed a specified

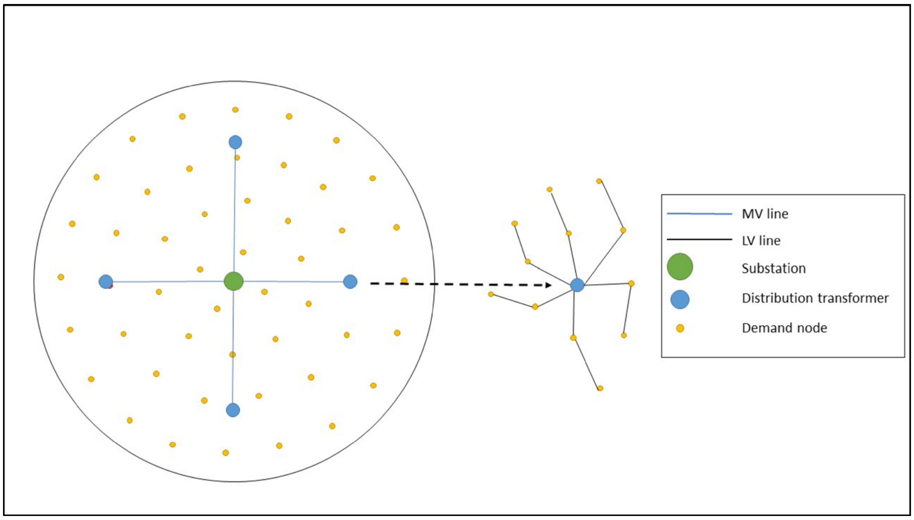

Fig. 4 Example of distribution network design in the version of OnSSET presnted by Korkovelos et al. [13], which introduced vector settlements in OnSSET, and design the distribution network assuming demand nodes are equally distributed within a circular settlement

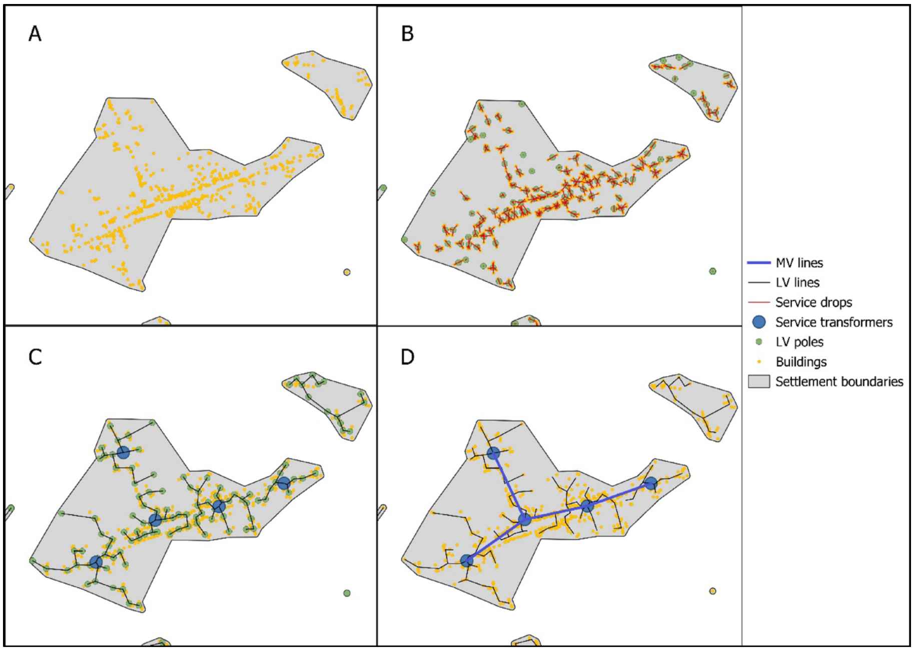

Fig. 5 Distribution network examples in the new detailed algorithm based on building footprints. **A** Building foot prints. **B** Placement of LV poles to connect all settlement with a service drop. **C** Placement of distribution transformers and MST of LV lines. **D** MST of MV lines to connect the distribution transformers. Note that only the largest settlement has a need for MV lines

length, L, and (ii) a maximum number of service drops, N, can stem from a single LV pole. The default values are set to 35 m and 10 service drops per pole respectively, based on [46]. A building is selected at random, and the N-1 closest buildings are identified. The center point of the N buildings is identified as the placement of the pole, and any building further than L away from the pole is not connected. The buildings that are connected to the pole are dropped from the list of buildings in the settlement, and the process is repeated until all buildings have been connected to an LV pole. Note that these LV poles do not represent all the LV poles in the settlement, but only the subset where the demand nodes are connected by a service drop.

2. Next, the number of distribution transformers are calculated, following the same constraints as in Korkovelos et al. [13]; the maximum power capacity of the transformer, the maximum number of connections per transformer and the maximum distance of LV lines. The LV poles are divided into the same number of service areas as the number of distribution transformer, and the center of each cluster is chosen for the placement of the distribution transformer(s).
3. For each service area, the minimum spanning tree (MST) connecting the LV poles to the distribution transformer is identified using PRIMs algorithm [47]. The MST reflects the LV network(s) within the settlement.

If more than one distribution transformer is required, the MST between the distribution transformers is calculated, reflecting the MV lines within the settlement.

2.3 Transmission network

The grid-extension algorithm in light version of OnSSET calculates for each settlement the cost of extending the grid from the closest point on the existing network, based on the electricity demand of the settlement and the extension distance. The cost of grid-extension combined with the cost of the distribution network and the cost of electricity generated for this centralized grid network is compared to the LCOE of the least-cost off-grid alternative in the settlement. If connection to the centralized grid is less costly than the least-cost off-grid alternative, the grid is extended there. Once all settlements have been evaluated, the process is repeated, taking into account the newly connected settlements when identifying the closets point on the network to extend from [13]. When calculating the cost of the potential grid-extension line(s), OnSSET takes into account information about distance to roads and substations, elevation, slope, and land cover in the settlements to assign a cost penalty to grid-extension between two nodes [12]. However, this approach remains simplified, assuming the lines connecting two cells or settlements follow a straight path, rather than the easiest path considering the geography between settlements.

In this paper, we introduce a more detailed algorithm for grid-extension based on a many-to-many implementation of the dijkstra algorithm[3]. The dijkstra algorithm has previously been used both for routing of new lines in geospatial electrification studies [48, 49] and for the estimation of existing MV lines in the Gridfinder tool [50]. The many-to-many implementation of the dijkstra algorithm finds the MST between multiple starting points and end points. The previous implementation of the algorithm used to identify existing MV network based on High-Voltage (HV) lines, night-time light, population data and road network found that the algorithm was 75% accurate based on a sample of 14 countries [50]. We therefore proceed to modify the same algorithm to identify the routing for extension of MV lines, modifying the algorithm for this purpose and enriching it with additional underlying GIS data. The update algorithm and its integration into OnSSET consists of four steps:

1. A cost raster is developed, whose weights indicate how difficult it is to extend the grid in each raster cell[4]. Based on a review of existing grid routing algorithms using various geospatial data [48–51], the cost raster developed in this paper combines roads, slope and land cover. The combined weights are assigned a value from 1 to 20, where 1 represents the easiest cells for the new grid to traverse (e.g. roads with no slope) and 20 the most difficult cells to traverse (e.g. rivers and water bodies). The classification and weights of each of the underlying GIS layers are described in Appendix A.
2. For each settlement, the maximum extension distance that would allow grid-connection (including distribution network and grid electricity generation) to be less costly than the least-cost off-grid alternative is calculated, considering the electricity demand in the settlement. Note that this distance could be negative, i.e. off-grid technologies are always less costly than grid-connection in a settlement due to the cost of the distribution network and cost of grid electricity generation.
3. The many-to-many dijkstra algorithm is applied, starting from the existing network and expanding to find the potential settlements to be connected (i.e. those that have a maximum extension distance larger than zero). Each time a target settlement is

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[3] The original algorithm developed by Facebook Inc. is available at https://github.com/facebookresearch/many-to-many-dijkstra.

[4] The resolution is an input to the algorithm, which was set to 50 m in this paper, ensuring that settlements will be located at different raster cells, given that this is smaller than the distance threshold used in the DBSCAN clustering algorithm.

identified, the distance that the dijkstra algorithm has traversed to find that settlement is compared to the maximum extension distance. If the traversed distance is larger, the settlement is dropped from the algorithm and will not be connected. If the distance is shorter, the settlement and the least-cost path identified by the dijkstra algorithm is added to the existing network.

4. Step 3 is repeated until no more settlements are connected to the grid network. Furthermore, three constraints have been included in the algorithm. First, the maximum distance that the MV network can be extended is implemented. This is a techno-economic consideration included also in the light version of OnSSET, with the default value set to 50 km as in [12]. That is, no targets are added to the network where the total extension distance found by the dijkstra algorithm is larger than 50 km from the original network. This distance limit acts as a proxy for higher losses and voltage drops with longer lines. To more accurately model this, a full load-flow analysis of the grid network would be required, which is beyond the scope of this analysis (and all but one of the existing geospatial electrification tools). The other two limitations are the maximum number of new connections that can be achieved during the time-step, and the maximum new power demand that can be supplied from the network during the time-step. If either of these constraints are reached during the connection of new settlements in the algorithm, the algorithm stops, and no new settlements are connected during this time-step. These constraints can be included to represent the practical limitations for grid-extension.

2.4 Mini-grid generation sizing

In the light version of OnSSET, mini grid sizing is based on the annual energy resource and demand. The peak load requirements in the settlement are calculated by dividing the annual electricity demand by the number of hours in a year, adjusting for transmission and distribution losses as required depending on technology, then dividing by an average-to-peak load factor [13]. Then the power capacity requirements are calculated as the peak load divided by the capacity factor of the technology, considering the local annual resource availability. This method of estimating capacity requirements can incorporate spatial variations in resource availability and electricity demand, to rapidly estimate LCOEs for many settlements across a geography. However, this simplified method of sizing technology capacities is not able to capture seasonal variations in either resource availability or demand, nor does it provide further insights into the reliability of the system or specific components of the system.

A more detailed hybrid mini-grid algorithm has been developed and incorporated in OnSSET in [52]. This algorithm simulates hybrid mini-grid systems using combinations of PV panels, diesel generator and batteries using an hourly resolution over one year. In each hour, the algorithm seeks to meet the electricity demand using PV, diesel or batteries, based on the availability of each component at that time and a set of dispatch rules described in [52]. Figure 6 displays an example demand and dispatch of the algorithm. If the simulated configuration meets the minimum criteria for reliability levels

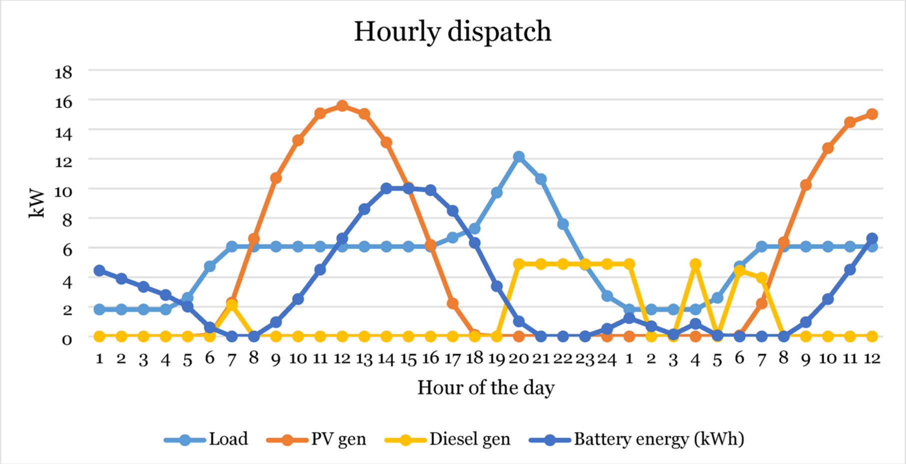

Fig. 6 Hourly load, PV generation, diesel and battery dispatch for an examined hybrid PV mini-grid configuration

and renewable share of electricity generation[5] over the year, the LCOE of electricity generation is calculated using costs and expected technology life on a component level. The battery life is calculated using a battery throughput model, based on the maximum number of full cycles possible for the battery type. Inverters and charge controllers are sized based on the other component. To find the optimal sizing of the generations system, a number of different configurations are simulated and the one that can meet the electricity demand and fulfill the criteria at the lowest LCOE is selected [52].

In this paper, the hybrid mini-grid sizing is enhanced with a Particle Swarm Optimization implementation to search through the solution space and identify the least-cost configuration of PV panels, diesel generator and batteries, rather than examining a fixed number of evenly spaced configurations within the solution space as in the previous implementation. A set of evenly spread particles, representing potential system configurations, act as a starting point. After these configurations are evaluated, the particles are guided by each other and move through the solution space to evaluate new configurations, until the minimum generation LCOE stabilizes, and an optimal or near-optimal configuration is identified.

The mini-grid sizing in the light version of OnSSET draws on annual energy resource data. The mini-grid optimization algorithm described above increases the temporal resolution by simulating the energy balance at an hourly rate. As such, this requires increased temporal resolution also of the input energy resource data. Sahlberg et al. [52] used an hourly solar resource profile of the whole country, and multiplied that profile by a scaling factor for each settlement based on the annual resource availability in the settlements. Here, we increase also the spatial resolution, by retrieving hourly solar irradiation data for multiple locations in the country. The data was retrieved for 2,464 evenly spaced points in the study area, at a distance of 0.1 degrees (approximately 11 km) between points. Each settlement then draws on the local solar resource availability from the closest of the 2,464 points. This approach better captures local variations in the solar resource over the year. The distance between points can be adjusted for a higher

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[5] The user can specify the desired thresholds for these criteria. In this paper, a hybrid mini-grid system must meet 98% of the annual demand and generate at least 50% of the electricity from renewable resources.

or lower spatial resolution, with data fetching times and storage requirements adjusting accordingly.

3 Study area and model setup

The original and new detailed modules are compared through a case-study of north-western DRC (Fig. 7). In the DRC as a whole, merely 19% of the population had access to electricity in 2020 [9]. Three centralized grids supply electricity in the country; one in the south-western parts, one in the south-eastern part and one in the east. The first two are interconnected through a High-Voltage (HV) DV line [53]. However, the three provinces included in this study (Nord-Ubangi, Sud-Ubangi and Mongala), are located more than 500 km from the closest HV line. Currently the electrification access in these provinces is low, with a significant portion of the population lacking access to reliable and affordable electricity. One of the key factors contributing to this is the limited infrastructure and the remote nature of many communities. The provinces' vast and often challenging geography, characterized by dense forests, rivers, and difficult terrains, poses significant logistical and technical difficulties in extending the electrical grid to remote areas. Despite the liberalization of the electricity sector in the DRC, and the presence of some investors in the development of solar and hydroelectric power plants in some other provinces of the country, these provinces have not yet experienced an improvement in their rate of access to electricity. The region's abundant natural resources, including rivers and sunlight, does however present opportunities for decentralized and off-grid renewable energy solutions to provide electricity to remote communities, and there are plans to install more than 100 mini-grids throughout the 145 territories in the country [54].

Mongala is one of the smallest of the 26 provinces of the DRC, further divided into three territories. The province has 1,740,000 inhabitants [55], approximately 80% of whom live in rural areas, and an electricity access rate of 1% [56]. North Ubangi is

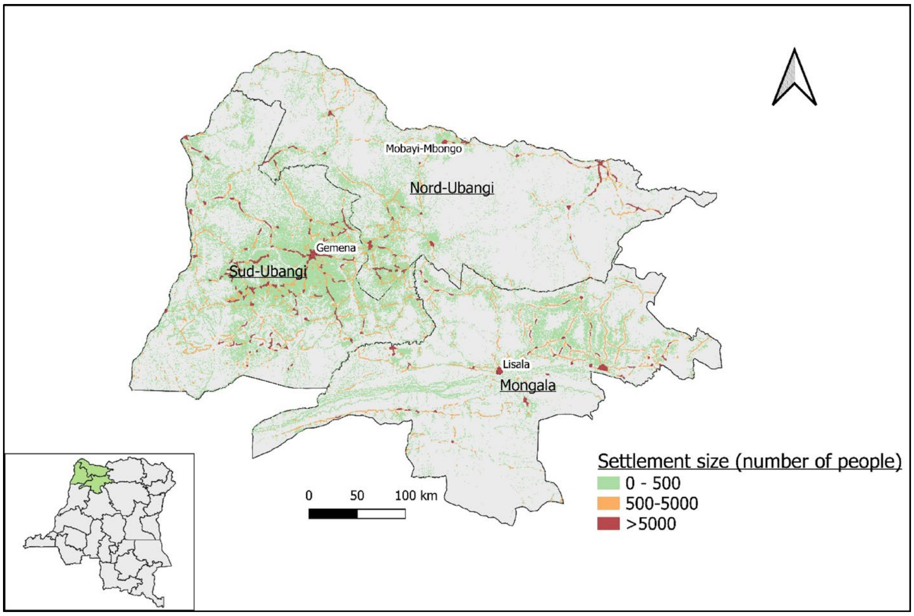

Fig. 7 The study area of the paper; the three provinces of Nord-Ubangi, Sud-Ubangi and Mongala and north-western DRC. The larger settlements are closely following the main roads in the area

Table 1 Scenario examined in this paper

Scenario	Improved distribution network	Improved grid-routing	Improved mini-grid optimization
Base			
Distribution	X		
Grid-routing		X	
Mini-grid			X
Full detail	X	X	X

"X" marks which of the new algorithms with increased detail are included in the scenario

Table 2 The five tiers of the Multi-Tier framework [61]

Tier	Household minimum daily electricity requirement	Potential services provided
1	12 Wh	Task lighting and phone charging
2	200 Wh	Lighting, phone charging, TV, fan
3	1 kWh	Tier 2 + medium power appliances
4	3.4 kWh	Tier 3 and high power appliances
5	8.2 kWh	Tier 3 and very high power appliances

located on the northern borders of the country, separated from the Central African Republic (CAR) by the Ubangi River. Nord Ubangi is also a predominantly rural province inhabited by just over a 1,270,000 inhabitants, divided between four territories [55]. The electricity access rate in the province is 5% [57]. Sud-Ubangi, has 2,460,000 inhabitants [55], with a higher population density than the other two provinces. The electrification rate is less than 1% in this province, which is split into four territories [58]. Only three mini-grids are identified in the study area (based on data from [59]), located in or around each of the province capitals. In this study, these metro-grids (i.e. larger mini-grids) act as starting points for the potential development of larger networks. The remaining settlements are assumed to be unelectrified in 2020, thus providing a suitable area for testing the impact of modelling detail as these settlements are candidates for either of the three technology types, while simultaneously providing insights into some of the most remote and least electrified areas of the DRC.

A base scenario is developed using the light version of the OnSSET tool[6], aiming at universal access to electricity in the region by 2030. The demand in each settlement in the base scenario is estimated using the Relative Wealth Index (RWI) [60]. The RWI was divided into five classes, and matched to the Tiers of the MTF, where the wealthiest areas were assigned the highest Tier and the least wealthy areas the lowest Tier. Following the development of the base scenario, each of the new more detailed algorithms described in Sect. 2.2–2.4 are incorporated individually to examine how they affect the least-cost technology mix in the region. Finally, all the new algorithms are included together to examine the combined effect on the least-cost technology split. The scenarios and their mapping to the new algorithms are seen in Table 1.

A sensitivity analysis is performed using the five demand Tiers (Table 2) to understand how the new modules impact the technology mix at different levels of demand. Demand has been shown to often be the most impactful factor for technology choice from previous geospatial electrification studies [12, 38, 42]. The demographic and techno-economic parameters used in the analysis, as well as the demand estimations for the base scenario, are found in Appendix B.

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[6] Version 1.1.a6, available at https://github.com/OnSSET/onsset/tree/v1.1a6.

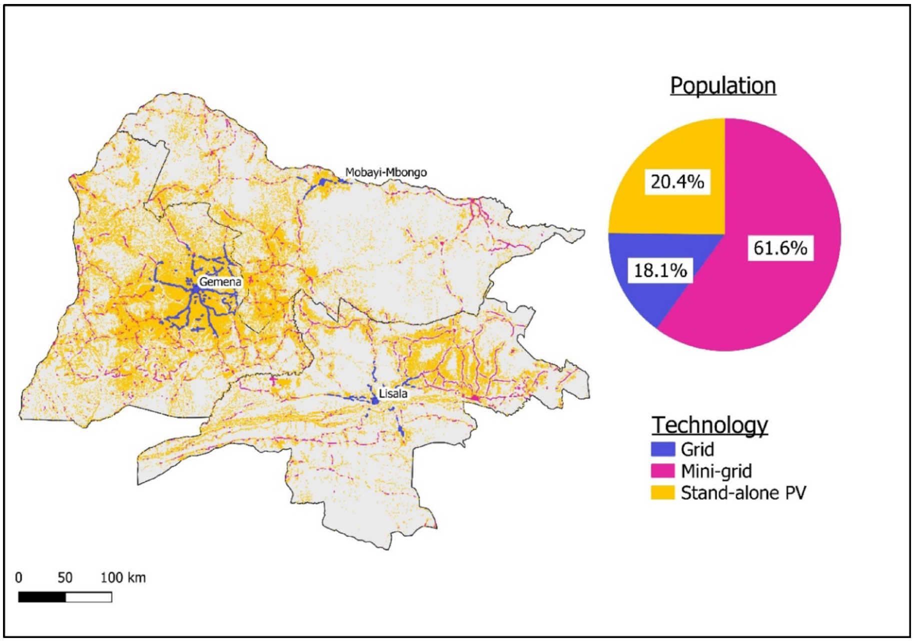
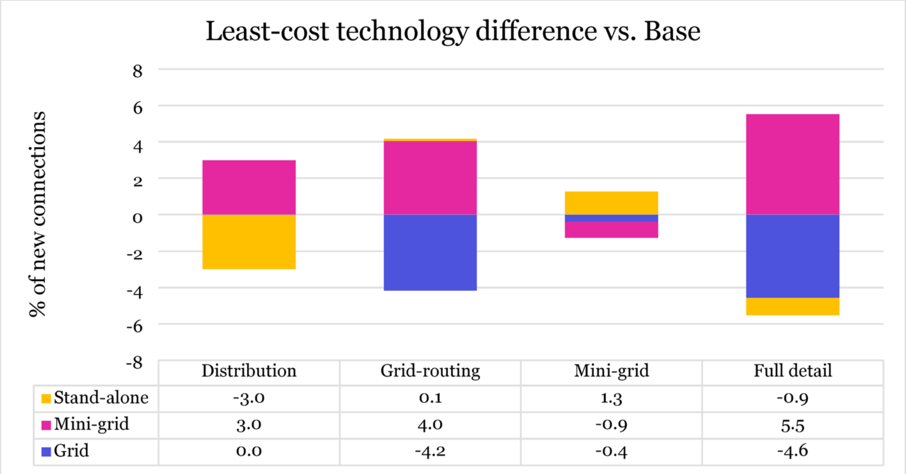


Fig. 8 Results of the base scenario. The three grids expand outwards around the three provincial capitals, mainly connecting the larger settlements located around the road network. Other larger settlements are supplied by mini-grids, whereas smaller settlements are supplied by SHS



	Distribution	Grid-routing	Mini-grid	Full detail
🟨 Stand-alone	-3.0	0.1	1.3	-0.9
🟪 Mini-grid	3.0	4.0	-0.9	5.5
🟦 Grid	0.0	-4.2	-0.4	-4.6

Fig. 9 Difference in the share of the new population connected per technology compared to the base scenario

4 Results and discussion

The Base scenario results display a mix of technologies being deployed by 2030 (Fig. 8). Almost one fifth (18%) of the population, located around the regional capitals, would be connected by the development of the regional grids. Mini-grids would serve more than half (62%) of the population, and SHS would be the least-cost option for the remaining 20% of the population. Grid-connection and mini-grids are deployed mainly for the larger settlements, where the demand is highest, and these technologies can draw on economies of scale compared to SHS.

Next, a comparison was made between the Base scenario and the scenarios with additional modelling detail. Figure 9 displays the change in population for each technology when the different detailed modelling modules were introduced, both individually and combined altogether. A general shift towards more mini-grids is seen with increased modelling detail, on behalf of a reduction in SHS and grid-connection. The only exception is in the Mini-grid scenario, where SHS increase on behalf of a reduction in grid and mini-grids. The changes observed in each scenario are presented in more detail below.

4.1 Distribution scenario results

The *Distribution* scenario led to a decrease in the population served at the lowest cost by SHS, met mainly by an increase in mini-grids as well as a smaller increase in grid-connection. This is caused by a lowering of the distribution network cost using the detailed modelling. The distribution network algorithm in the light version of OnSSET assumes settlements are circular and demand nodes are evenly spread out within the settlement. However, as demand nodes are generally clustered within the settlements (to varying extents), the length of lines required to connect them are often shorter. Furthermore, the light version designs the LV lines to connect all the way to all the demand nodes (Fig. 4). The detailed model considers that the LV line can be located up to 35 m away from a demand node, as the last distance is covered by the service drop. The Distribution scenario resulted in a 16% reduction in the length of the network required for all settlements in the area, causing 3% of the population to shift from SHS to mini-grids.

4.2 Grid-routing scenario results

The *Grid-routing* scenario led to a decrease in grid-connections, met by an increase in both mini-grids and SHS technologies. This is mainly caused by the maximum distance limit imposed on MV lines. Figure 9 displays the new grid lines using the original grid-extension algorithm as introduced in [13] (left), and the new lines from the updated detailed grid-routing in this paper (right). In both cases, some lines reach the maximum distance of 50 km. In the original algorithm, where straight lines are considered, this extends to settlements that are located further away from the starting point in Lisala compared to the updated grid-routing which largely follows the curved road network. Hence, the updated grid algorithm does not reach as far from the starting point, causing fewer settlements to be connected to the grid.

Two additional scenarios were run with the distance limit increased to 100 km, using the light and detailed grid extension algorithms. In both cases the number of people connected to the grid increased, to 38.4% and 36.3% of the total population for the light and detailed algorithm respectively. That is, the trend in reduced grid-connections with the detailed grid routing remains, but the difference is reduced from 4.2% to 1.9%.

Two additional observations were made by comparing the light and detailed grid-extension algorithms. First of all, the light algorithm results in some lines to nearby settlements that are almost parallel from the starting point (see Fig. 10A). In the real case, these would most likely be combined at the start and branch off at a later stage (as in Fig. 10B). Secondly, there is a difference in which settlements get connected to the grid, which can most clearly be observed south of Lisala. This is caused by a combination of the distance limit, the fact that both algorithms are iterative and affected by the direction of extension in the early iterations, and the fact that the dijkstra algorithm takes into account the whole route between settlements. As observed in Fig. 10, the highest cost penalties are seen south of Lisala where the Congo River flows. This obstacle is not

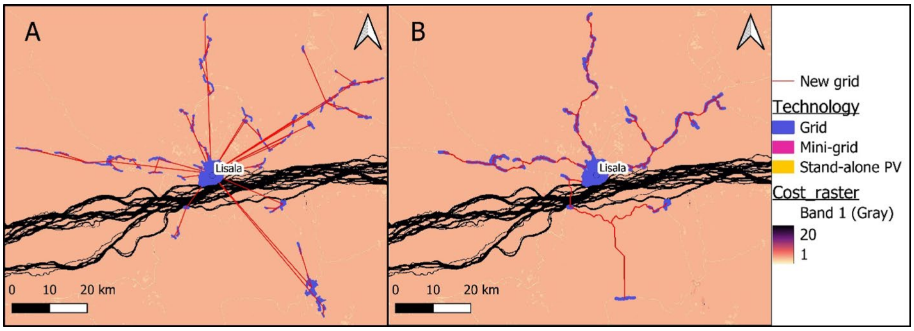


Fig. 10 Expansion of the grid-network to new settlements around Lisala. **A** The algorithm for grid-extension in the light version of OnSSET. **B** The updated detailed grid-routing algorithm presented in this paper. Note that the highest values in the cost raster used for the dijkstra algorithm in the updated grid-routing (B) reflect the Congo Rover that passes south of Lisala. In the light algorithm, near-parallel lines are extended from Lisala to settlements that are close to each other in some cases, where each of the settlements have a high enough demand to justify grid-extension. Also, the detailed grid algorithm better captures the difficulties associated with extending the grid across the river

fully captured by the grid-extension in the light version of OnSSET, which crosses the river at four different points. In the updated algorithm based on the dijkstra algorithm the Congo River is crossed only at one point west of Lisala. Thus, the settlements in the south-east are not connected as the total extension distance in this case becomes longer than the 50 km limit. It should be noted that both algorithms evaluate one settlement at a time. That is, they examine for each settlement whether the grid can extend from the current network and provide electricity at a lower cost than the least-cost alternative. However, there may be cases where nearby settlements do not individually have sufficient demand to make grid-extension less costly than off-grid, but if considered together the combined demand could make grid-extension viable.

4.3 Mini-grid scenario results

The Mini-grid scenario displays an overall increase in SHS (1.3%), and a decrease in both mini-grids (-0.9%) and grid (-0.4%). Here, there are two technology shifts occurring simultaneously from the new mini-grid optimization algorithm. In some settlements, the cost of mini-grids are reduced, causing mini-grids to replace grid-extension. In others, the cost of mini-grids are increased, causing SHS to replace mini-grids. The detailed algorithm provide additional details on the sizing of the generation system of mini-grids down to the component level, and can also incorporate additional constraints such as reliability levels and emission constraints. This also reflects on the data requirements. Energy resource data and demands are required on an hourly level, and the costing data is required per component instead of USD/kW for the system as a whole as in the light version. Thus the shift in technology is not only caused by the difference in algorithms for mini-grid generation sizing, but also the different costing data used. Running the *Mini-grid* scenario instead with the same component costing data as seen in version 2.0 of the Global Electrification Platform, increases the share of mini-grids (9.2%) on behalf of both grid (-6.3%) and SHS (-2.9%).

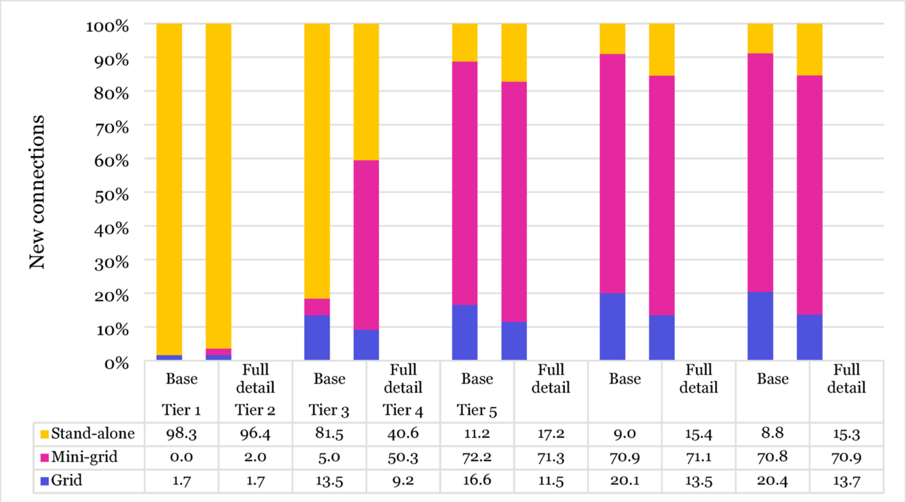
4.4 Full detail scenario results

In the *Full detail* scenario, the combined effect leads to more mini-grids (5.5%), and less grid-connection (-4.6%) and SHS (-0.9%). These scenarios have the largest increase in mini-grids. This can be explained by the fact that at least two of the detailed modules favor mini-grids; the detailed distribution modelling cause mini-grids to replace SHS, and the detailed grid-routing cause mini-grids to replace grid-connection. Notably, the combined effect of the three detailed modules does not equal the sum of the change of each module, as the effects of these interact. E.g. mini-grids may become less competitive compared to SHS in some settlements by using the detailed mini-grid optimization algorithm, but at the same time more competitive compared to SHS in the same settlements by the detailed distribution network algorithm. As such, the change in SHS in the *Full detail* scenario (-0.9%) does not equal the sum of the changes in SHS observed in the *Distribution* (-3.0), *Grid-routing* (0.1) and *Mini-grid* (1.3) scenarios.

4.5 Sensitivity analysis

A sensitivity analysis was undertaken to understand the impacts of increased modelling also at other demand levels. The previous analysis was repeated, but at demand levels uniformly varied from Tier 1 to Tier 5 for all settlements rather than individually assessed based on the RWI. Figure 11 displays the least-cost technology mixes at each Tier for the Base and Full detail scenarios. The full results per Tier level are found in Appendix C. Key insights are presented below:

- The *Distribution* scenarios leads to a reduction in SHS across Tier 1 – Tier 3, mainly met by an increase in mini-grids. At Tier 4 and Tier 5 demand levels, only the smallest settlements are electrified by SHS at the lowest cost, and there was no notable effect from the new distribution sizing algorithm on the technology mix.
- The *Grid-routing* scenarios leads to a reduction in the population connected to the grid, replaced by SHS at Tier 2 demand levels and mainly by mini-grids at Tier 3–5 demand levels. At Tier 1 there was no grid-extension using either the light or detailed grid extension algorithm, as the low demand does not lead to any grid-extension using either the light or detailed algorithm.
- The *Mini-grid* scenarios displayed varying results by demand level. At Tier 1, the low demand levels meant mini-grids were not chosen using either the light or detailed



	Base Tier 1	Full detail Tier 2	Base Tier 3	Full detail Tier 4	Base Tier 5	Full detail	Base	Full detail	Base	Full detail
🟨 Stand-alone	98.3	96.4	81.5	40.6	11.2	17.2	9.0	15.4	8.8	15.3
🟪 Mini-grid	0.0	2.0	5.0	50.3	72.2	71.3	70.9	71.1	70.8	70.9
🟦 Grid	1.7	1.7	13.5	9.2	16.6	11.5	20.1	13.5	20.4	13.7

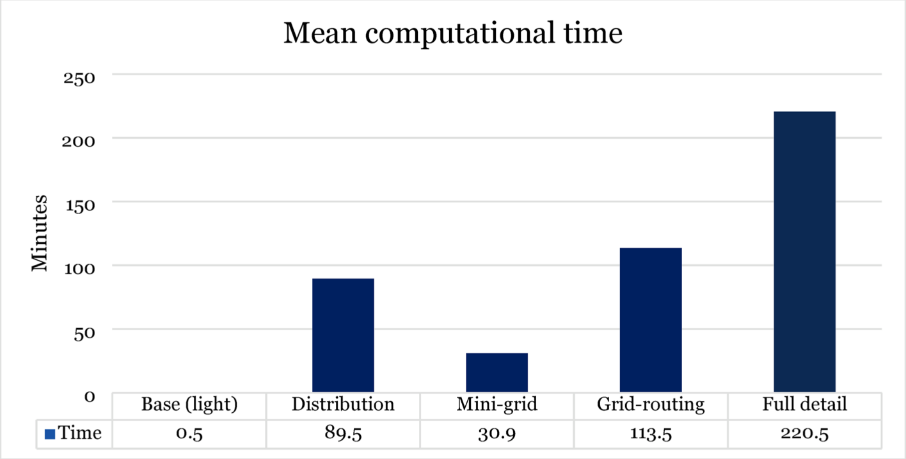
Fig. 11 Least-cost electricity supply technology split (percent of newly connected population in the area) at different demands and modelling detail

algorithm for mini-grid sizing. At Tier 2, there was an increase in mini-grids on behalf of SHS, whereas at Tier 3 and above there was a decrease of mini-grids on behalf of SHS.

- The *Full detail* scenarios see an increase in mini-grids at Tier 1 and 2 demands, and a reduction in mini-grids at Tier 3 demands. Grid-connection remains unchanged at Tier 1 but reduces at Tier 2 and above. SHS decreases at Tier 1 and 2 but decreases at Tier 3–5 (Fig. 11).
- By far the largest variations are seen at Tier 2 demand, where there is a shift mainly from SHS to mini-grids, and to a smaller extent also from grid-connection to mini-grids. At other Tiers, no technology change by more than 6.7%. Altogether, demand is still a key driver of technology choice, but the increased modelling detail shifts the dynamic where the transition between the least-cost technologies happens.

4.6 Computational time and modelling detail

The computational time was compared while running the model at different levels of detail. The average time of the six demand levels run using the different scenarios are presented in Fig. 12. On average, including at least one of the detailed modules increased computational times by more than two orders of magnitude, except for the Mini-grid scenarios, which were 62 times slower than the Base scenarios on average. The scenarios in this paper were run with a PC with an Intel Xeon E5-1650 processor running at 3.50 GHz and 64 GB RAM. The study area measures 162,874 sq. km, and contains 91,103 settlement clusters. The exact computational times for a geospatial analysis will vary depending on several factors, related to computational resources, the volume of population settlements, the extent of the existing power network, the maximum grid extension threshold and other inputs which affect the iterative grid extension algorithm etc. Notably, not all algorithms in OnSSET increase linearly with the area covered or number of settlements. Still, understanding the magnitude of how the more detailed modules affect computational times can be useful for the choice of experimental design in geospatial electrification studies.



	Base (light)	Distribution	Mini-grid	Grid-routing	Full detail
■ Time	0.5	89.5	30.9	113.5	220.5

Fig. 12 Mean computational time at different levels of modelling detail using OnSSET. The more detailed algorithms increase the computational time compared to the light version of OnSSET used in the Base scenario by more than one order of magnitude in the Mini-grid scenario, and more than two orders of magnitude in the others

There are significant data gaps and uncertainties related to geospatial electrification modelling and scenario design [38]. Sensitivity analysis or approaches for robust decision-making that aim to overcome these issues may require a very large number of simulations. E.g. Sahlberg et al. developed a scenario-discovery approach using OnSSET, based on 1,944 simulations [38], and Khavari et al. developed a global sensitivity analysis from 2,080 simulation which was replicated for three countries for a total of 6,240 simulations [42]. While such experiments can still be performed using the detailed model presented in this paper, the computational resources or time allotted need to be vastly increased as compared to the light version of the OnSSET model. There is a general link between computational time and modelling detail in geospatial electrification tools [34]. Thus, this trade-off is very likely the same for other tools, although the exact difference may vary. Therefore, the choice of geospatial electrification tool and modelling detail should consider the purpose of the analysis as well as data availability and the type of scenario and sensitivity analysis to be developed.

5 Conclusions

In this paper we introduce improved, more detailed modules, in the OnSSET tool for geospatial electrification analysis. Doing so, we create a flexible tool that can provide both rapid first-pass assessments of least-cost electricity supply options in an area, as well as more granular analysis with routing of transmission and distribution networks and design of hybrid mini-grids based on hourly energy balances, at the cost of increased computational time. We also study the effect on least-cost technology split using the existing lighter version of the tool and the more detailed modules developed in this paper through a case-study of the DRC. The case study presented here serves as an illustrative example of the general trends observed. E.g. differences in computational times observed in this study can illustrate the orders of magnitude of change with varying modelling detail, but this can vary largely between regions depending on the total area modelled, starting electrification rate, extent of the existing network, etc. Similarly, settlement patterns vary among countries and could change the effect of more detailed distribution network sizing.

The results of the case study display a shift in the least-cost technology split with increased modelling detail. The detailed sizing of the distribution network causes a general reduction in the length and cost of these networks, which causes a shift from SHS towards mini-grids and grid-extension. Improved routing causes a reduction in the number of settlements connected by grid-extension, replaced by mini-grids or SHS. The detailed mini-grid optimization displayed varying results at different demand levels.

These findings are of importance for geospatial electrification analysis aimed at the achievement of SDG 7. The results of this paper highlight how different model methodologies affect the identified least-cost technology mix. This relates not only to the level of modelling detail, but also to assumptions and approaches of different geospatial electrification tools. The choice of geospatial electrification tool should also consider the data availability and uncertainty, scenario development approach the state of electrification in the study area. Explorative analysis drawing on multiple simulations, which could be more beneficial for an area with low electrification rate, is more likely to benefit from using a rapid first-pass geospatial electrification tool to start with, whereas analysis closer to actual project developments, which could be more suitable for areas with higher electrification rates, is more likely to benefit from the more detailed geospatial electrification tool classes.

The developments introduced in this paper means that the OnSSET tool fulfills most of the requirements of what Ciller and Lumbreras [11] classifies as *intermediate analysis tools*. However, the algorithms developed in this paper do not include a full load-flow analysis as required for a *detailed generation and network design tool*. Including a load-flow analysis could further affect the design of the distribution networks and which settlements can economically be connected to the grid, taking into account all of the power constraints. Including a load-flow analysis would enable the removal of the techno-economic distance limit considered for grid-extension, which proved to have a significant effect on technology choice. A few additional limitations of the present study and areas for future research should also be highlighted. First, distribution networks are often designed to follow the road networks within the settlement [46]. This was not included in the MST for distribution network in this paper, as no openly available road dataset with this level of granularity could be identified. Furthermore, MSTs provide the shortest possible network and may therefore underestimate the length of lines compared to real-world networks. On the other hand, it is assumed that all households in the community would be served by the mini-grid. In reality, buildings on the outskirts of the community or low-demand buildings may be left unserved or connected by SHS, reducing the length of the network. Secondly, building footprints were assumed to represent households, and assigned the same demand levels within settlements. Granular data on the type of buildings and demand estimations on a building level constitute important areas for future research. Finally, component costing for mini-grids have been assumed uniform for all mini-grids. Costs can vary depending on economies of scale [62], and also depending on transport and accessibility. Unfortunately, costing data disaggregated by size or number of mini-grids could not be identified. Finally, it is worth noting that this paper compares the effect of modelling detail within one tool. A comparison of results using identical, or close to identical, input parameters using different geospatial electrification tools could be valuable for analysts and decision-makers planning to make use of a geospatial electrification analysis.

Appendix A

Cost raster for grid routing algorithm.

Factors that can have an impact on the cost of grid-extension include existing power lines, roads, land cover, slope, elevation, wind speed and built environment [51]. Previous studies have developed grid routing algorithms using different selections of these factors [48–51]. In this algorithm, three GIS layers have been used to define the weights; roads, slope and land cover. Particular focus was given to the local conditions in DRC, namely the significant river networks and dense vegetation that may affect grid routing possibilities. However, the open-source algorithm allows the datasets and weights to be modified to capture the key factors in the region of interest. The classifications of the cost raster are seen in Tables 3 and 4, and an example of the cost raster in the study area is seen in Fig. 13.

Table 3 Classification based on land cover, water and road network

Land type	Weight
Major roads (Motorway, trunk, primary, secondary)	1
Minor roads (Tertiary, residential, service, unclassified)	2
Sparsely vegetated areas (Bare ground, Rangeland, Crops)	3
Densely vegetated areas (Trees)	4
Built environment	5
Wet areas (Flooded vegetation, Snow/Ice)	10
Water	20

Table 4 Slope multipliers, added to the classifications in table 3

Slope (degrees)	Multiplier
0–5	1
5–10	1.25
10–20	1.5
> 0	2

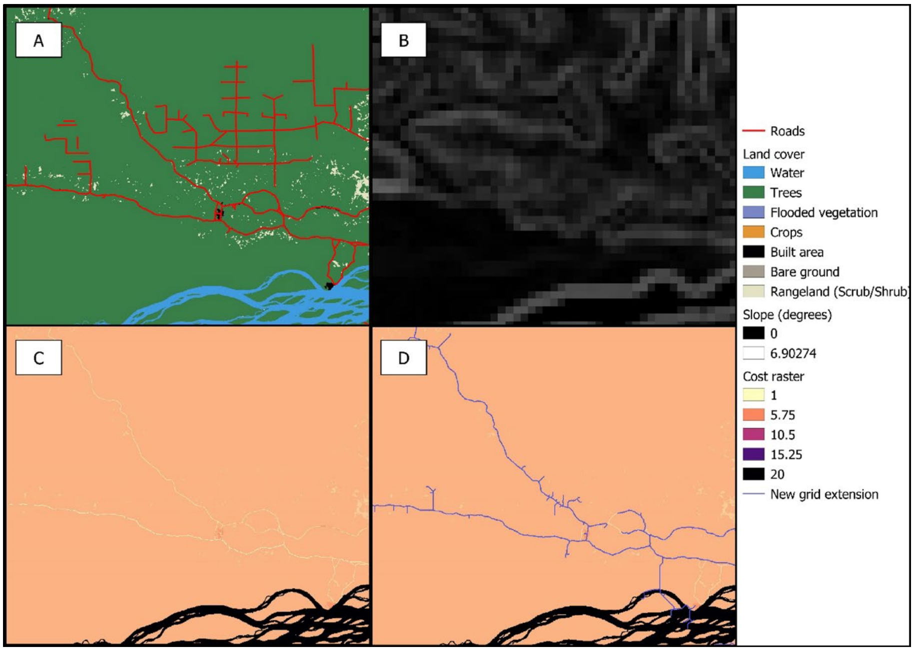


Fig. 13 Cost raster. **A** Land cover and road network. **B** Slope. **C** Cost raster created from the input datasets. **D** Cost raster and example of new grid extension

Table 5 Demographic parameters

Parameter	Value
Average household size	5.2 people / household [63]
Population growth	3.5% / year [64]

Appendix B

Model inputs and demand.

See Tables 5, 6, 7, 8 and 9.

Table 6 Investment costs for off-grid technologies, based on information from [13, 65–68]

Parameter	Value
PV mini-grid cost	2,950 USD/kW
Hydro mini-grid cost	3,000 USD/kW
Wind mini-grid cost	3,750 USD/kW
PV standalone system (< 0.02 kW)	9,620 USD/kW
PV standalone system (0.02 < kW < 0.05)	8,780 USD/kW
PV standalone system (0.05 < kW < 0.1)	6,380 USD/kW
PV standalone system (0.1 < kW < 1)	4,470 USD/kW
PV standalone system (> 1 kW)	6,950 USD/kW

Table 7 Mini-grid component costs. 2020 and 2030 estimates based on [62, 69]

Component	Cost
PV panel + Balance of System	596 USD/kWp
Battery (Li-ion)	297 USD/kWh
Battery inverter	303 USD/kW
Diesel generator	261 USD/kW

Table 8 Transmission and distribution parameters, based on [4, 6, 15, 18, 23, 70–74]

Parameter	Value
HV line – 69 kV	53,000 USD/km
MV line – 33 kV	7,000 USD/km
LV line – 0.24 kV	4,250 USD/km
Distribution transformer – 50 kVA	4,250 USD
Grid transmission and distribution losses	12%
Mini-grid distribution losses	5%
Grid electricity generation cost	0.10 USD / kWh

Appendix C

Sensitivity analysis on impact of modelling detail at different demand levels.

See Figs. 14, 15, 16, 17 and 18.

Table 9 Geospatial datasets used in the electrification model

Dataset	Use	Source
Building footprints	Used as a basis for estimating the population distribution for the settlement clusters.	Open Buildings [43]. Available at https://sites.research.google/open-buildings/
Administrative boundaries	Delineates the geographical boundaries of the analysis	GADM version 4.1 [75]. Available at https://gadm.org/download_country.html
Existing mini-grid locations	Used to identify existing electricity infrastructure, to identify which settlements are electrified in the start year of the analysis.	Mini-Grid Databse (MGDB 1.0) [59]. Available at https://minigrids.org/market-report-2020/
Roads	Existing roads, used to specify grid extension suitability.	OpenStreetMap [76], available through https://www.openstreetmap.org/.
Elevation	The elevation map is used in order to determine the terrain slope. Both the terrain slope and the elevation are used in order to specify the grid extension suitability.	CGIAR Consortium for Spatial Information (CGIAR-CSI) [77], available at http://srtm.csi.cgiar.org/srtmdata/
Land cover	The land cover map classifies the study area into 17 land cover classes. This affects the suitability for grid extension	10 m Annual Land Use Land Cover (9-class) [78], available at https://planetarycomputer.microsoft.com/dataset/io-lulc-9-class
Global Horizontal Irradiation (GHI)	Annual GHI (kWh/m^2/year), used to identify the availability and cost of PV systems.	Global Solar Atlas [79], available at https://globalsolaratlas.info/
Wind speed	Annual average wind speed (m/s), used to identify the availability and cost of wind-powered hybrid mini-grids.	Global Wind Atlas [80], available at https://globalwindatlas.info/
Hydropower potential	Points showing potential mini/small hydropower potential for mini-grids	KTH [81], available at https://energydata.info/dataset/small-and-mini-hydropower-potential-in-sub-saharan-africa
Travel time	Visualizes spatially the travel time required to reach from any individual cell to the closest town with a population of at least 50,000 people. Used to calculate the transport cost of diesel.	Malaria Atlas Project [82], available at https://malariaatlas.org/explorer/#/

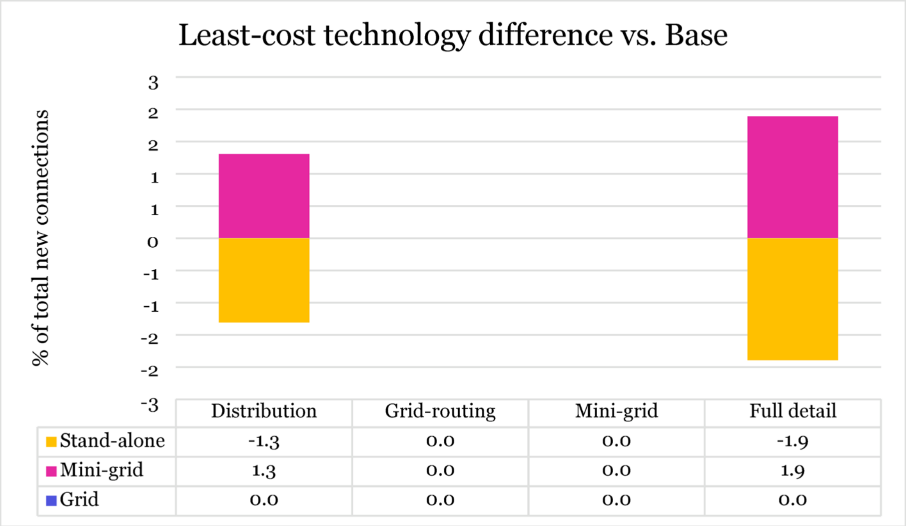
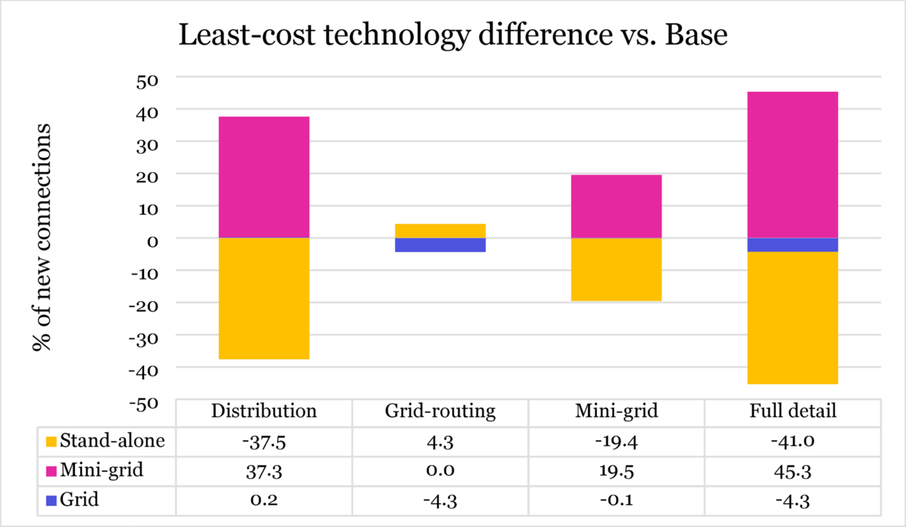
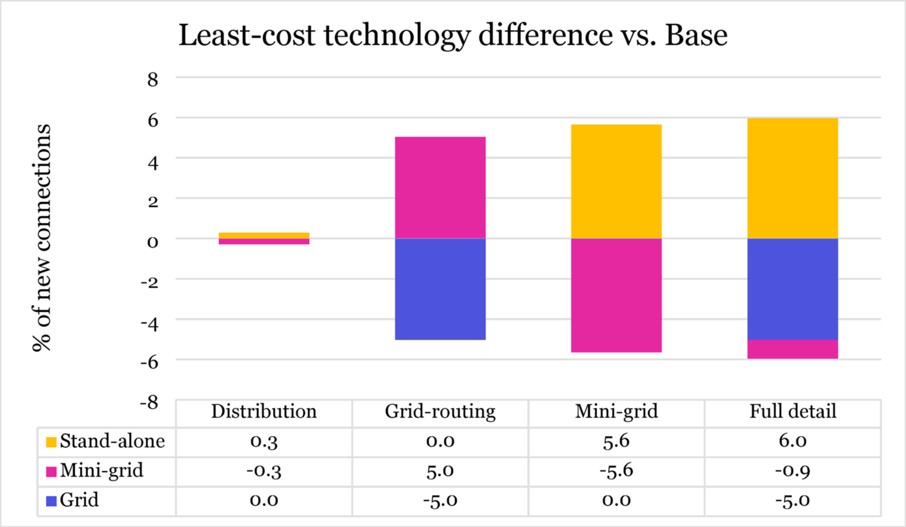


Fig. 14 Change in technology vs. base scenarios at Tier 1 levels of electricity demand



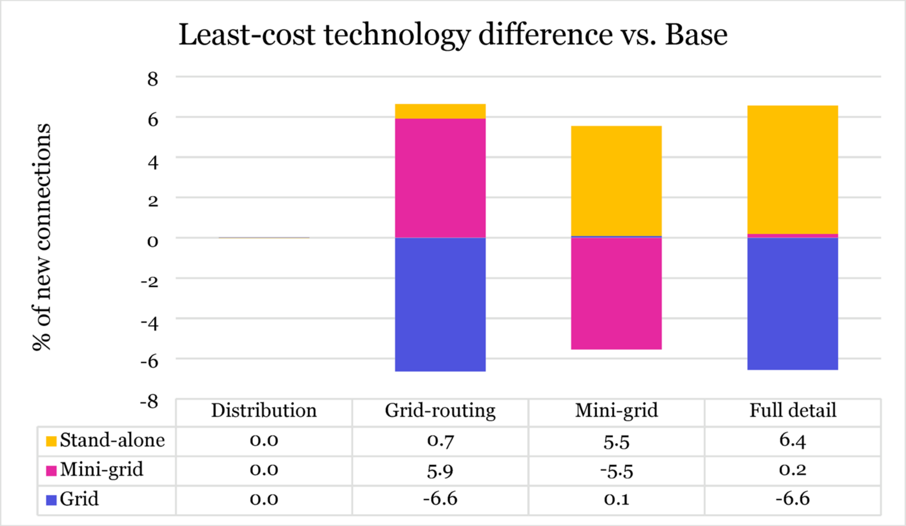
	Distribution	Grid-routing	Mini-grid	Full detail
🟨 Stand-alone	-37.5	4.3	-19.4	-41.0
🟪 Mini-grid	37.3	0.0	19.5	45.3
🟦 Grid	0.2	-4.3	-0.1	-4.3

Fig. 15 Change in technology vs. base scenarios at Tier 2 levels of electricity demand



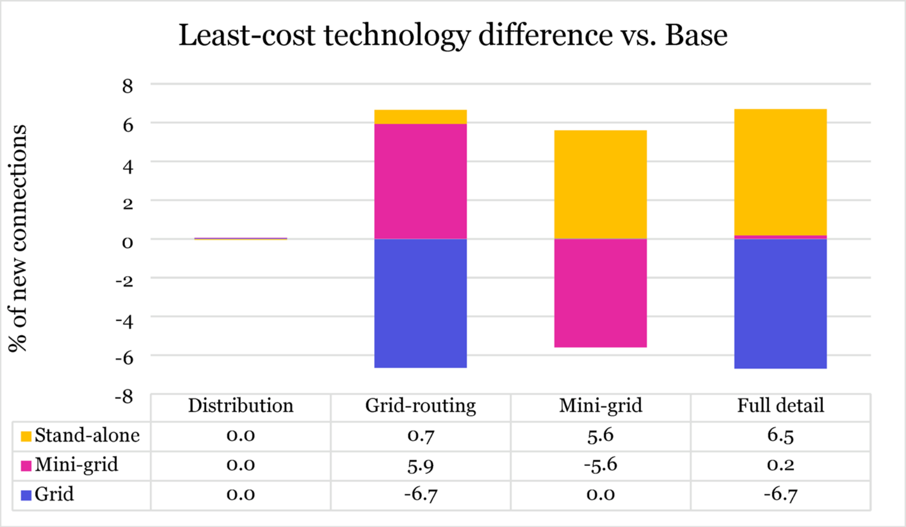
	Distribution	Grid-routing	Mini-grid	Full detail
🟨 Stand-alone	0.3	0.0	5.6	6.0
🟪 Mini-grid	-0.3	5.0	-5.6	-0.9
🟦 Grid	0.0	-5.0	0.0	-5.0

Fig. 16 Change in technology vs. base scenarios at Tier 3 levels of electricity demand



	Distribution	Grid-routing	Mini-grid	Full detail
🟨 Stand-alone	0.0	0.7	5.5	6.4
🟪 Mini-grid	0.0	5.9	-5.5	0.2
🟦 Grid	0.0	-6.6	0.1	-6.6

Fig. 17 Change in technology vs. base scenarios at Tier 4 levels of electricity demand



	Distribution	Grid-routing	Mini-grid	Full detail
🟨 Stand-alone	0.0	0.7	5.6	6.5
🟪 Mini-grid	0.0	5.9	-5.6	0.2
🟦 Grid	0.0	-6.7	0.0	-6.7

Fig. 18 Change in technology vs. base scenarios at Tier 5 levels of electricity demand

Author contributions

AS contributed with Conceptualization, Methodology, Software, Formal analysis, Investigation, Visualization, Data curation, Writing—original draft, Writing—review & editing. AK contributed with Writing—review & editing, CT and CK contributed with Data curation, Writing—review & editing. BK contributed with Software, Writing—review & editing. FFN contributed with Supervision, Writing—review & editing. All authors read and approved the final manuscript.

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Data availability

The light version of OnSSET is available at https://github.com/OnSSET/onsset/tree/v1.1a6. The OnSSET code used to run the scenarios and files required to re-run the OnSSET scenarios are openly available at https://github.com/OnSSET/onsset/tree/flexible-detail. The input parameters and geospatial datasets are listed in Appendix B.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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References

1. Ormerod RJ. Energy models for decision making. Eur J Oper Res. Dec. 1980;5(6):366–77. https://doi.org/10.1016/0377-2217(80)90123-X.
2. Hoffman KC, Wood DO. Energy System Modeling and Forecasting, *Annu. Rev. Energy*, vol. 1, no. 1, pp. 423–453, Nov. 1976, https://doi.org/10.1146/annurev.eg.01.110176.002231
3. Dodds PE, Keppo I, Strachan N. Characterising the evolution of energy system models using model archaeology. Environ Model Assess. Apr. 2015;20(2):83–102. https://doi.org/10.1007/s10666-014-9417-3.
4. Sustainable Energy for, All. Integrated Electrification Pathways for Universal Electricity Access: A Primer, 2019. Accessed: Feb. 11, 2023. [Online]. Available: https://www.seforall.org/system/files/2019-06/SEforALL_IEP_2019.pdf
5. The Sustainable Development Goals Report 2022, 2022. Accessed: Aug. 12, 2022. [Online]. Available: https://unstats.un.org/sdgs/report/2022/The-Sustainable-Development-Goals-Report-2022.pdf
6. Fuso Nerini F, et al. Mapping synergies and trade-offs between energy and the sustainable development goals. Nat Energy. Jan. 2018;3(1):10–5. https://doi.org/10.1038/s41560-017-0036-5.
7. IEA IRENA, UNSD, World Bank, WHO, Tracking SDG 7: The Energy Progress Report, Bank. Washington, DC, 2023. Accessed: Jun. 06, 2023. [Online]. Available: https://trackingsdg7.esmap.org/data/files/download-documents/sdg7-report2023-full_report.pdf
8. IEA IRENA, World Bank, UNSD, WHO Tracking SDG 7. : The Energy Progress Report 2021, 2021. Accessed: Nov. 04, 2021. [Online]. Available: https://trackingsdg7.esmap.org/data/files/download-documents/2021_tracking_sdg7_report.pdf
9. IEA IRENA, World Bank, UNSD, WHO, Tracking SDG 7: The Energy Progress Report (, Bank. Washington, DC, 2022. Accessed: Nov. 28, 2022. [Online]. Available: https://trackingsdg7.esmap.org/data/files/download-documents/sdg7-report2022-full_report.pdf
10. Mentis D, et al. The benefits of Geospatial planning in energy access – A case study on Ethiopia. Appl Geogr. Jul. 2016;72:1–13. https://doi.org/10.1016/j.apgeog.2016.04.009.
11. Ciller P, Lumbreras S. Electricity for all: the contribution of large-scale planning tools to the energy-access problem. Renew Sustain Energy Rev. Mar. 2020;120:109624. https://doi.org/10.1016/j.rser.2019.109624.
12. Mentis D, et al. Lighting the world: the first application of an open source, Spatial electrification tool (OnSSET) on Sub-Saharan Africa. Environ Res Lett. Jul. 2017;12:085003. https://doi.org/10.1088/1748-9326/aa7b29.
13. Korkovelos A, Khavari B, Sahlberg A, Howells M, Arderne C. The role of open access data in Geospatial electrification planning and the achievement of SDG7. An OnSSET-Based case study for Malawi. Energies. Jan. 2019;12(7):1395. https://doi.org/10.3390/en12071395.
14. Moksnes N, Korkovelos A, Mentis D, Howells M. Electrification pathways for Kenya–linking Spatial electrification analysis and medium to long term energy planning. Environ Res Lett. Sep. 2017;12(9):095008. https://doi.org/10.1088/1748-9326/aa7e18.
15. International Energy Agency (IEA). World energy outlook 2019. Paris, 2019.
16. IEA. World Energy Outlook 2017, Paris, 2017. [Online]. Available: https://www.iea.org/reports/world-energy-outlook-2017
17. IEA. World Energy Outlook 2022, Paris, 2022. [Online]. Available: https://www.iea.org/reports/world-energy-outlook-2022
18. ESMAP. Global Electrification Platform | ESMAP. https://www.esmap.org/global-electrification-platform-gep (accessed Feb. 09, 2023).
19. KTH Royal institute of Technology, Kartoza, and, Recon. Preparation of an indicative least cost Geospatial electrification plan. To Achieve Universal Access In Somalia; 2021.
20. World Bank. Project Information Document-Integrated Safeguards Data Sheet -Madagascar - Least-Cost Electricity Access Development Project -LEAD -P163870. 2019. [Online]. Available: -Project-LEAD-P163870.pdf http://documents1.worldbank.org/curated/en/281861547039951916/pdf/Project-Information-Document-Integrated-Safeguards-Data-Sheet-Madagascar-Least-Cost-Electricity-Access-Development
21. ESMAP and World Bank. Benin electrification platform. Global Electrification Platf Explorer. https://benin.gep.kartoza.com/gep (accessed Mar. 23, 2023).
22. Page Arias A. IntiGIS 2.0: Objetivos y propuesta metodológica. Análisis de competitividad tecnológica en Ghana, 2015. Accessed: Mar. 23, 2023. [Online]. Available: https://eprints.ucm.es/id/eprint/33324/1/TFM_AlbaPage.pdf
23. Moner-Girona M, Bódis K, Huld T, Kougias I, Szabó S. Universal access to electricity in Burkina faso: scaling-up renewable energy technologies. Environ Res Lett. Aug. 2016;11(8):084010. https://doi.org/10.1088/1748-9326/11/8/084010.
24. Moner-Girona M, et al. Decentralized rural electrification in kenya: speeding up universal energy access. Energy Sustain Dev. Oct. 2019;52:128–46. https://doi.org/10.1016/j.esd.2019.07.009.
25. Kemausuor F, Adkins E, Adu-Poku I, Brew-Hammond A, Modi V. Electrification planning using network planner tool: the case of Ghana. Energy Sustain Dev. Apr. 2014;19:92–101. https://doi.org/10.1016/j.esd.2013.12.009.
26. Parshall L, Pillai D, Mohan S, Sanoh A, Modi V. National electricity planning in settings with low pre-existing grid coverage: Development of a spatial model and case study of Kenya, *Energy Policy*, vol. 37, no. 6, pp. 2395–2410, Jun. 2009, https://doi.org/10.1016/j.enpol.2009.01.021

27. Rural and Renewable Energy Agency. Rural Energy Strategy and Master Plan for Liberia Until 2030, 2016. Accessed: Sep. 15, 2021. [Online]. Available: https://gestoenergy.com/wp-content/uploads/2018/04/LIBERIA-RURAL-ENERGY-STRATEGY-AND-MASTER-PLAN.pdf
28. Gesto Energy. Senegal's SE4All Rural Electrification - Action Agenda and Investment Prospectus, 2018. Accessed: Nov. 18, 2022. [Online]. Available: https://gestoenergy.com/wp-content/uploads/2019/04/Gesto_Senegal_EN.pdf
29. Innovation Energie Development, Catalogue Logiciels IED. 2023. [Online]. Available: https://www.ied-sa.com/solutions/planification/geosim
30. Ellman D. The reference electrification model: A Computer Model for Planning Rural Electricity Access.
31. Mwalenga LM. A comprehensive computer-aided planning approach for universal energy access : case study of Kilifi, Kenya, 2015. [Online]. Available: https://dspace.mit.edu/handle/1721.1/103572
32. Drouin C. Geospatial cost drivers in Computer-aided electrification planning: The Case of Rwanda.
33. González-García A, Ciller P, Lee S, Palacios R, de Cuadra F, García, Pérez-Arriaga JI. A rising role for decentralized solar minigrids in integrated rural electrification planning? Large-Scale, Least-Cost, and Customer-Wise design of grid and Off-Grid supply systems in Uganda. Energies. Jan. 2022;15(13):4517. https://doi.org/10.3390/en15134517.
34. Morrissey J. Achieving universal electricity access at the lowest cost: A comparison of published model results, *Energy Sustain. Dev.*, vol. 53, pp. 81–96, Dec. 2019, https://doi.org/10.1016/j.esd.2019.09.005
35. Sustainable Energy for All. Data Standards for Integrated Energy Planning, 2020. [Online]. Available: https://www.seforall.org/system/files/2020-10/IEP-data-standards_0.pdf
36. Nerini FF, Broad O, Mentis D, Welsch M, Bazilian M, Howells M. A cost comparison of technology approaches for improving access to electricity services. Energy. Jan. 2016;95:255–65. https://doi.org/10.1016/j.energy.2015.11.068.
37. Khavari B, Korkovelos A, Sahlberg A, Howells M, Fuso Nerini F. Population cluster data to assess the urban-rural split and electrification in Sub-Saharan Africa. Sci Data. Apr. 2021;8(1):117. https://doi.org/10.1038/s41597-021-00897-9.
38. Sahlberg A, Khavari B, Korkovelos A, Fuso Nerini F, Howells M. A scenario discovery approach to least-cost electrification modelling in Burkina Faso. Energy Strategy Rev. Nov. 2021;38:100714. https://doi.org/10.1016/j.esr.2021.100714.
39. Pappis I et al. Feb., Influence of Electrification Pathways in the Electricity Sector of Ethiopia—Policy Implications Linking Spatial Electrification Analysis and Medium to Long-Term Energy Planning, *Energies*, vol. 14, no. 4, p. 1209, 2021, https://doi.org/10.3390/en14041209
40. van Ruijven BJ, Schers J, van Vuuren DP. Model-based scenarios for rural electrification in developing countries. Energy. Feb. 2012;38(1):386–97. https://doi.org/10.1016/j.energy.2011.11.037.
41. School of Geography and Environmental Science, University of Southampton;, Department of Geography and Geosciences, University of Louisville, Departement de Geographie, Universite de Namur, and Center for International Earth Science Information Network (CIESIN). Columbia University, WorldPop. Global High Resolution Population Denominators Project - Funded by The Bill and Melinda Gates Foundation (OPP1134076). 2018. [Online]. Available: https://doi.org/10.5258/SOTON/WP00670
42. Khavari B, Sahlberg A, Usher W, Korkovelos A, Fuso Nerini F. The effects of population aggregation in Geospatial electrification planning. Energy Strategy Rev. Nov. 2021;38:100752. https://doi.org/10.1016/j.esr.2021.100752.
43. Sirko W et al. Continental-Scale Building Detection From High Resolution Satellite Imagery.
44. Ester M, Kriegel H-P, Sander J, Xu X. A Density-Based Algorithm for Discovering Clusters in Large Spatial Databases with Noise.
45. Edelsbrunner H, Kirkpatrick D, Seidel R. On the shape of a set of points in the plane, *IEEE Trans. Inf. Theory*, vol. 29, no. 4, pp. 551–559, Jul. 1983, https://doi.org/10.1109/TIT.1983.1056714
46. Costa JL. Geospatial Optimisation Methods for Mini-grid Distribution Networks, 2022, [Online]. Available: https://kth.diva-portal.org/smash/get/diva2:1698359/FULLTEXT01.pdf
47. Prim RC. Shortest connection networks and some generalizations. Bell Syst Tech J. Nov. 1957;36(6):1389–401. https://doi.org/10.1002/j.1538-7305.1957.tb01515.x.
48. Holistic geospatial data-based procedure for electric network design and least-cost energy strategy, Energy Sustain. Dev., vol. 58, pp. 1–15. Oct. 2020, https://doi.org/10.1016/j.esd.2020.06.008
49. Geiger AN, Cader C. Bestimmung optimaler stromnetzerweiterung in ländlichen gebieten Mithilfe von Routing-Algorithmen, p. 6.
50. Arderne C, Zorn C, Nicolas C, Koks EE. Predictive mapping of the global power system using open data. Sci Data. Jan. 2020;7(1):19. https://doi.org/10.1038/s41597-019-0347-4.
51. Monteiro C, Ramirez-Rosado IJ, Miranda V, Zorzano-Santamaria PJ, Garcia-Garrido E, Fernandez-Jimenez LA. GIS spatial analysis applied to electric line routing optimization, *IEEE Trans. Power Deliv.*, vol. 20, no. 2, pp. 934–942, Apr. 2005, https://doi.org/10.1109/TPWRD.2004.839724
52. Khavari B, Sahlberg A. Geo-spatial electricity demand assessment & hybrid off-grid solutions to support electrification efforts using onsset: the case study of Tanzania, p. 67.
53. World Bank. Increasing access to electricity in the Democratic Republic of congo. Washington, DC: World Bank; 2020. https://doi.org/10.1596/33593
54. IFC Launches Work on Scaling Mini-Grid. Program to Increase Clean Electricity Access in the DRC, *IFC*. https://ifcpressreleasesprod.aseprod.ifc.org/all/pages/PressDetail.aspx?ID=26877 (accessed Jun. 01, 2023).
55. Agence Nationale pour la Promotion des Investissements. Provinces. https://www.investindrc.cd/fr/Provinces?debut_articles=9#pagination_articles (accessed Jun. 02, 2023).
56. Omasombo Tshonda J, Ambwa J-C, Stroobant É, Mumbanza mwa Bawele J, Krawczyk J, Laghmouch M. Mongala - Jonction des territoires et bastion d'une identité supra-ethnique, Musée royal de l'Afrique centrale, ISBN 978-9-4922-4416-1, 2015. Accessed: Jun. 02, 2023. [Online]. Available: https://www.africamuseum.be/sites/default/files/media/docs/research/publications/rmca/online/monographies-provinces/mongala.pdf
57. Tshonda JO et al. Nord-Ubangi - L'État-Zaïre englué dans l'identité ethnique de Mobutu, Musée royal de l'Afrique centrale, ISBN: 978-9-4926-6962-9, 2019. Accessed: Jun. 02, 2023. [Online]. Available: https://www.africamuseum.be/sites/default/files/media/docs/research/publications/rmca/online/monographies-provinces/nord-ubangi.pdf
58. Tshonda Omasombo J, Nagifi Deamo V, Léonard G, Krawczyk J, Laghmouch M, Simons E. Sud-Ubangi - bassins d'eau et espace agricole, Musée royal de l'Afrique centrale, ISBN 978-2-87593-014-9, 2013. [Online]. Available: https://www.africamuseum.be/sites/default/files/media/docs/research/publications/rmca/online/monographies-provinces/sud_ubangi_2.pdf

59. Mini-Grid Databse (MGDB 1.0). BloombergNEF. 2020. [Online]. Available: https://minigrids.org/market-report-2020/
60. Chi G, Fang H, Chatterjee S, Blumenstock JE. Microestimates of wealth for all low- and middle-income countries, *Proc. Natl. Acad. Sci.*, vol. 119, no. 3, p. e2113658119, Jan. 2022, https://doi.org/10.1073/pnas.2113658119
61. Bhatia M, Angelou N. Beyond Connections: Energy Access Redefined. 2015. [Online]. Available: https://openknowledge.worldbank.org/handle/10986/24368
62. ESMAP. 2022 Mini Grids for Half a Billion People: Market Outlook and Handbook for Decision Makers, World Bank, Washington, DC, Sep. 2022. doi: 10/P1751510dd4ab407e083a6098d1905fa94f.
63. United Nations Population Division. Database on Household Size and Composition 2022. 2022. Accessed: May 11, 2023. [Online]. Available: https://www.un.org/development/desa/pd/data/household-size-and-composition
64. United Nations, Department of Economic and Social Affairs, Population Division. World Population Prospects: The 2022 Revision, 2022. (accessed May 11, 2023). https://population.un.org/wpp/
65. International Renewable Energy Agency. Renewable power generation costs in 2017. UAE: IRENA, Abu Dhabi; 2018.
66. International Renewable Energy Agency. Innovation Outlook: Renewable Mini-Grids, 2016.
67. International Renewable Energy Agency. Solar PV in Africa: Costs and Markets, 2016.
68. Korkovelos A, et al. A Geospatial assessment of Small-Scale hydropower potential in Sub-Saharan Africa. Energies. Nov. 2018;11(11):3100. https://doi.org/10.3390/en11113100.
69. Energy Sector Management Assistance Program. Mini grids for half a billion people: market outlook and handbook for decision makers. World Bank; 2019. https://doi.org/10.1596/31926.
70. Korkovelos A, et al. Supporting electrification policy in fragile states: A Conflict-Adjusted Geospatial least cost approach for Afghanistan. Sustainability. Jan. 2020;12(3):777. https://doi.org/10.3390/su12030777.
71. Energy Sector Management Assistance Program (ESMAP). Model for Electricity Technology Assessment (META). The World Bank, 2014.
72. Karhammar R, et al. Sub-Saharan africa: introducing Low-cost methods in electricity distribution networks. Energy Sector Management Assistance Program (ESMAP); 2006.
73. Energy Sector Management Assistance Program (ESMAP). Reducing the Cost of Grid Extension for Rural Electrication, Washington, DC, 2000.
74. International Energy Agency (IEA). Energy Access Outlook 2017: From Poverty to Prosperity, International Energy Agency, Paris, 2017. Accessed: Jan. 24, 2021. [Online]. Available: https://www-oecd-ilibrary-org.focus.lib.kth.se/docserver/9789264285569-en.pdf?expires=1611503833&id=id&accname=oid023441&checksum=058D3685FC70F07A6465A26F63C2A1E8
75. GADM GADM. Database of Global Administrative Areas v. 3.4, 2018.
76. OpenStreetMap contributors. Geofabrik https://www.geofabrik.de/
77. CGIAR-CSI. SRTM Data. https://srtm.csi.cgiar.org/srtmdata/
78. Impact Observatory. 10m Annual Land Use Land Cover (9-class), 2022. (accessed May 11, 2023). https://planetarycomputer.microsoft.com/dataset/io-lulc-9-class
79. Solargis. Global Solar Atlas 2.0. https://globalsolaratlas.info/
80. DTU Technical University of Denmark. Global Wind Atlas 3.0. https://globalwindatlas.info/
81. KTH Royal institute of Technology. Sub Saharan Africa - Small and mini hydropower potential, 2016. https://energydata.info/dataset/small-and-mini-hydropower-potential-in-sub-saharan-africa
82. Weiss DJ et al. Jan., A global map of travel time to cities to assess inequalities in accessibility in 2015, *Nature*, vol. 553, no. 7688, pp. 333–336, 2018, https://doi.org/10.1038/nature25181

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