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Lighting the World: the first application of an open source, spatial electrification tool (OnSSET) on Sub-Saharan Africa

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Abstract

In September 2015, the United Nations General Assembly adopted *Agenda 2030,* which comprises a set of 17 Sustainable Development Goals (SDGs) defined by 169 targets. 'Ensuring access to affordable, reliable, sustainable and modern energy for all by 2030' is the seventh goal (SDG7). While access to energy refers to more than electricity, the latter is the central focus of this work. According to the World Bank's 2015 Global Tracking Framework, roughly 15% of the world's population (or 1.1 billion people) lack access to electricity, and many more rely on poor quality electricity services. The majority of those without access (87%) reside in rural areas. This paper presents results of a geographic information systems approach coupled with open access data. We present least-cost electrification strategies on a country-by-country basis for Sub-Saharan Africa. The electrification options include grid extension, mini-grid and stand-alone systems for rural, peri-urban, and urban contexts across the economy. At low levels of electricity demand there is a strong penetration of standalone technologies. However, higher electricity demand levels move the favourable electrification option from stand-alone systems to mini grid and to grid extensions.

1. Introduction

Access to electricity services is one prerequisite for sustainable development and a powerful factor in poverty alleviation. Yet, in 2015 over 1.1 billion people globally are without electricity access [1]. The majority of the unserved (nearly 97%) live in Sub-Saharan Africa and in developing Asia. With an electrification rate of just 43%, Africa has, by far, the lowest rate globally, well below the global average of 82%. Developing Asia (83%), the Middle East (93%) and Latin America (95%) follow [2]. The lowest electrification rates in all regions are in rural areas [3].

Although the importance of energy services for economic and social development has long been recognized [4], energy was not one of the Millennium Development Goals (MDGs). The MDGs have now been replaced by Agenda 2030 for Sustainable Development. The Agenda includes a set of 17 sustainable development goals (SDGs) with 169 associated targets for 2030. The Agenda lists sustainable energy as a SDG in its own right. SDG7 reads: 'Ensuring access to affordable, reliable, sustainable and modern energy for all by 2030' [5].

The objectives of this paper are to: [1] demonstrate the usefulness of open-source geospatial electrification to provide insights for electrification planning in 44 Sub-Saharan African countries, and [2] derive a least cost solution for infrastructure development and resulting generation mix using local relevant information. The analysis introduces the novel, open-source spatial electrification tool (OnSSET) and considers varying electricity consumption targets, expressed as tiers of access as defined by the World Bank [6].

A number of local or national electrification studies have been undertaken. From early efforts to electrify cities and farms [7] to recent national efforts [8, 9], these studies provide local perspectives or roadmaps that at best indicate the challenges ahead for the subcontinent but cannot be generalized as blue prints for sub-continent electrification.

To date, continent wide electrification studies have been an exception [10]. A general paucity of reliable energy data, especially in the least developed countries, is the main reason for the lack of such assessments [11]. Unlike traditional energy supply studies, electrification analyses require spatially specific information such as renewable energy flows, hydro power sites, location of transmission lines, sizes, and locations of settlements and their distances from the nearest electric grids. Such information is usually absent in national energy databases. Modern remote sensing techniques can help fill, or at least narrow, the information gap [12, 13]. Such techniques that capture the spatial dimension of energy systems are essential for the development of spatially inclusive and comprehensive energy demand and supply analyses.

This paper presents novel extensions to electrification planning methodologies, drawing on geospatial information systems (GIS) tools, i.e. datasets derived from satellite imagery and from a plethora of existing maps to fill data gaps [14]. This methodology is a powerful tool for the design of more effective electrification strategies in developing countries [15].

This paper is structured as follows: we briefly describe GIS applications used for energy planning in the remainder of section 1. Section 2 formulates the electrification expansion methodology, listing and analysing the datasets underlying this study. Section 3 presents the results of this work. Section 4 concludes and suggests areas for further work.

1.1. GIS and energy planning

Energy access and associated infrastructure development planning cannot be addressed without regard of the spatial nature and dynamics of human settlements and economic production [16, 17]. Data requirements increase dramatically for spatial energy analyses compared with traditional energy analyses while data availability becomes increasingly sparse. GIS tools are increasingly becoming the methodology of choice, encouraged with increasing open data availability [17].

Within a context where energy services are increasingly delivered in a decentralized manner and through non-state actors, energy planners and researchers gradually use GIS analysis in order to define national or sub-national electrification plans and subsequent strategies and policies. Tiba *et al* [18] developed a GIS-based decision support tool for renewable energy planning in rural areas. The tool allows planning of a sizeable addition of renewable energy technologies and the management of the already installed systems. Diverse criteria are considered in order to identify the most favourable location for installing new energy systems. These criteria include solar and wind availability, proximity to transmission network, rural electrification index, income per capita and others. This study though considers mainly the implementation of solar and wind power technologies, overlooking the potential penetration of other technologies (for instance grid expansion or mini hydropower) to provide electricity to unserved areas.

In this direction, Amador *et al* [19] highlight a major problem of rural electrification, which is the selection of the most suitable technology. GIS is used to categorize zones into areas that are more appropriate for either conventional or renewable technologies based on techno- economic criteria. The authors use the levelized cost of generating electricity, LCOE, as the metric of choice. In this analysis four parameters are considered and related to costs: rural population density (inhabitants km^{-2}), annual solar irradiation, annual average wind speed ($m\,s^{-1}$) and distance of connection to the MV grid (km). This tool has been applied in the municipality of Lorca in Murcia, Spain and verified with coherent results. However, the limited use of GIS data (including the electrical network map, housing map, wind and solar resource maps) and the lack of a grid expansion costing algorithm constitute some key weaknesses of this effort.

A noteworthy study that investigates energy solutions in rural Africa is introduced by [20]. A spatial electricity cost model is designed to indicate whether diesel generators, photovoltaic systems or grid extension are the least-cost options in off-grid areas. This analysis points out where grid extensions constitute the cost optimal option based on a set of boundaries that delineate the distance where a potential extension would be feasible, i.e. 10, 30 and 50 km distance from low (LV), medium (MV) and high voltage (HV) lines respectively. These boundaries are however not result of an optimization exercise and should be further examined.

Another substantial effort is undertaken by [21] who uses a GIS approach for demand driven rural electrification planning in Uganda, allocating an energy benefit point system to priority sectors (education and health) based on local conditions and available resources in each area. However, this study does not suggest an optimal way to provide electricity to the identified priority areas. [22] introduce a framework that combines mobile phone data analysis, socioeconomic and geospatial data and state-of-the art energy infrastructure engineering techniques to assess the feasibility of a limited number of different electrification options (three) for rural areas, such as extensions of the medium voltage (MV) grid, diesel engine-based micro grids and stand-alone solar photovoltaic (PV) systems.

Similarly, the Network Planner approach [23] considers demand centres and compares the implications of either extending the national grid or rolling out solar PV household systems backed up by diesel generators for productive uses or opting for low voltage diesel based mini-grid systems. The model has been applied to Liberia, Ghana [24] and Nigeria [25]. Nonetheless, this tool accounts for a limited number of electrification technologies, considers a limited number of demand nodes and accounts for a static representation of the bulk electricity generation mix.

In the same way, [26] developed the Reference Electrification Model (REM), which extracts information from several GIS datasets in order to determine where extending the grid is the most cost-effective option and where other off grid systems, such as micro grids or stand-alone solar systems, would be more economical. However, the technical potential of renewable energy resources is not scrutinized and the resolution of the analysis is limited to broad administrative areas.

Other geospatial applications (not published in the academic literature) are available in open web platforms. The International Finance Corporation has developed an off-grid market opportunity tool [27]. This tool uses geospatial information (such as population density, proximity to transmission and road network and others) to help private companies, governments, academia and civil society to develop a high-level view of where markets for off-grid electrification may exist to better inform decision-making. Similarly, the Energy Commission of Ghana developed an energy access toolkit for monitoring and evaluating energy access and renewable energy resources in the country using geospatial datasets [28]. However, no electrification analysis is included in these applications in order to identify the cost optimal electrification technology.

To summarise, the majority of the previously developed GIS methods have one or more of the following limitations: they focus on how rural areas should be electrified; they do not provide an overall electrification expansion indication for an entire country; they deploy a limited number of electrification technologies; they use a limited number of GIS data (some of which proprietary) and with that limit analysis; they use a limited number of demand nodes; they lack a grid expansion costing algorithm or they do not account for a dynamic change of the bulk grid electricity supply mix.

We advance the most recent analysis, combining and adapting a simplified technology choice and cost topology [9] and GIS approach used in [8] to employ open data sets to assess electrification options and costs to meet different demand levels. To do this, it was necessary to overcome limitations of the latter. Those shortcomings included that:

- It was spatially limited to Nigeria—while Africa's most populous nation, it does not provide the macro information required to mobilise action [39] for initiatives such as Sustainable Energy for All (SE4All) [40] or Power Africa [41].
- It analysed limited consumption targets and scenarios—simply assuming urban and rural consumption levels. Electrification cost and technology choice change substantially as a function of the tier of access [9]. A view on cost per tier was missing.
- It relied on locally derived information (which may not be available for all countries); while that might have improved data quality, it does not allow for rapid global replication. The latter, if executed in an open modular framework, would allow both global coverage and an improved assessment assuming data could simply replace global data sets.
- As no extensive spatially explicit mini and small hydropower potential maps were available previously, its potential was not evaluated. However, its potential is significant and, indicated in a first of its kind analysis in this work.

In this paper a spatially explicit continent wide model (at a 1 by 1 km grid size equal to the highest resolution dataset of continental population density and distribution [42]) that establishes the cost, technology choice (in the form of (a) grid extension, (b) mini grid, and (c) stand-alone options) to meet different tiers of electricity consumption by settlement is used for first time. It relies on available global data sets and a simplified method for rapid assessment. However, the methodology is modular permitting data to be easily replaced or the method improved. Key parameters include: population density, local grid connection conditions and proximity, energy resource endowment and locally differentiated technology costs, national grid electricity cost obtained from The Electricity Model Base for Africa [43].

2. Methodology

Due to its spatially explicit information and often intuitive visualisation potential, GIS modelling holds great promise for informing policy formulation and decision making with regards to energy planning [17, 44]. The methodology and the main steps pursued in this study are summarized in the flow chart below (see figure 1). It is based on [8] and [9] with specific additions in bold.

Specific changes include the use of Open Street Map data to determine transmission and power plant location information, where local information is not available. Additional costs are assigned to the electricity grid expansion process based on the topology of the studied area. In order to develop demand scenarios, 'tiers' of access are incorporated. As

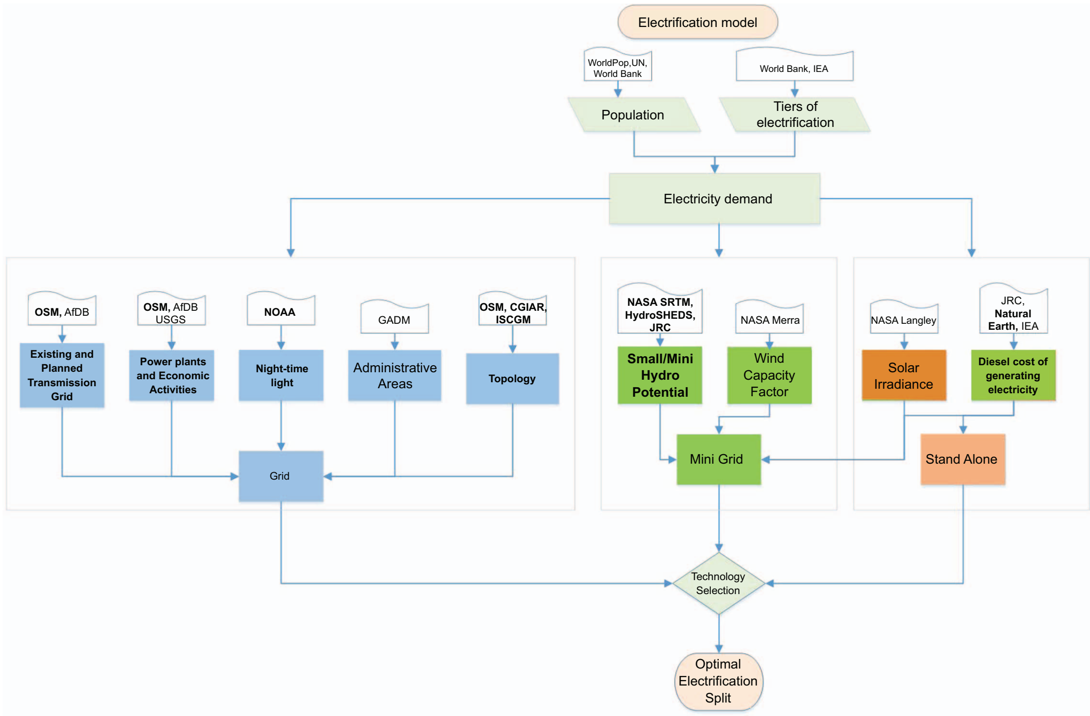

Figure 1. Framework of the Open Source Spatial Electrification Toolkit (OnSSET) and principal data sources.

no global mini and small hydro potential dataset exists, one is developed based on several datasets. Moreover, night-time light datasets are used in combination with the population distribution, the transmission and road network in order to identify the presently electrified populations [45, 46]. In this analysis, the costing of each technology considers the topological characteristics of the subjected area, e.g. areas on higher elevation would indicate an additional investment cost due to higher construction and transportation costs. Likewise, proximity to the road network, land cover, slope gradient and distance from substations affect the initial investment cost [47] (detailed presentation in the appendix). Finally, coastline information is adopted to calibrate a heuristic for diesel costing. The modular approach (indicated in figure 1) allows for data sets to simply be replaced when more accurate or updated information is available.

2.1. Electricity demand

Geospatial data entailing the administrative boundaries throughout 44 countries in Sub-Saharan Africa [48], population density [42] which is 'assigned' to point locations of 1 by 1 km, hereinafter called settlements, existing infrastructure (transmission lines) [49, 50] and national access to electricity [2] are processed to derive information about the current electrification status by country. Thereafter, the transmission grid is assumed to expand to connect with planned power plants and mineral mining sites [49–51]. The population is adjusted to reflect the population projected for 2030 by [52]. Population combined with different tiers of electrification leads to future electricity demand scenarios—a crucial input to the cost-optimal allocation of electrification options. Each tier represents different levels of electricity services provided, starting from basic lighting (lowest tier) to services that provide comfort, such as air-conditioning (table 1). Various tiers are assessed for all given grid points in order to capture different specificities of electricity demand levels per region. In this paper results are presented as if each tier was homogeneously applied over the continent. In reality though, significant income differences across the continent would imply different electricity demand levels and all five tiers are likely to co-exist in a given country. For a more detailed analysis, interested users may therefore navigate through the open source code and the results available on GitHub[9] and select location specific tiers.

2.2. Assigning costs

The electrification options analysed in the study included three categories: grid connections, mini-grid systems and stand-alone systems. For every GIS cell, the levelized cost of generating electricity (LCOE) of these options are evaluated by a simple cost model based on Nerini *et al* 2016 [9]. The resulting LCOE information is fed into the GIS model to determine the most economical option for each grid cell given its geospatial characteristics. In this analysis, two different international oil prices are considered (current or low and projected or high) in order to assess how

[9] https://github.com/KTH-dESA/PyOnSSET.

Table 1. Mapping of tiers of electricity to indicative services [6].

Level of access	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Indicative appliances powered	*Torch and radio*	*Task lighting + phone charging or radio*	*General lighting + air circulation + television*	*Tier 2 + light appliances (i.e. general food processing and washing machine)*	*Tier 3 + medium or continuous appliances (i.e. water heating, ironing, water pumping, rice cooking, refrigeration, microwave)*	*Tier 4 + heavy or continuous appliances (i.e. air conditioning)*
Consumption per capita and year (kWh)	—	8	44	160	423	598

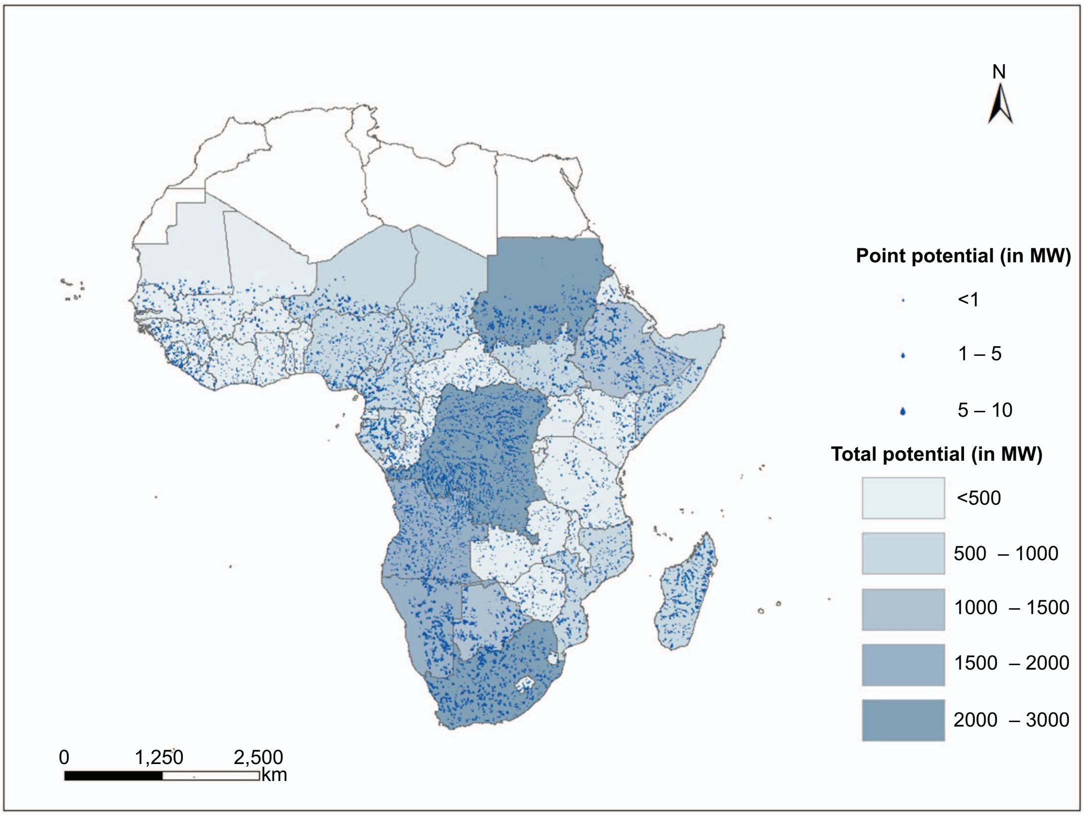

Figure 2. Mini and small hydro power potential in the selected 44 Sub-Saharan countries.

increasing oil prices influence the least cost electrification mix. The current oil price is 47 US$/bbl [53], while the projected one reaches 113 US$/bbl according to the IEA New Policies Scenario [54]. More information can be found in the appendix.

2.3. Spatial energy resource availability

As information relating to diesel price heuristics, wind and solar potential represent only modest additions in this piece, they are included in the appendix. However, as no extensive GIS small and mini-hydro power potential maps exist on the entire subcontinent, we develop an analysis to generate a map of estimated potentials, with their location (figure 2).

Small and mini hydro power potentials[10] were derived by combining and analysing several publicly available GIS datasets: digital elevation map [55], global river network [56], Global Streamflow Characteristics Dataset [57, 58], inland water bodies and restriction zones [59].

Digital elevation maps at 90 m spatial resolution (0.00083^{o}) were processed to obtain water flow directions, layers of flow accumulation raster and estimations of the drainage area per cell. Combined

[10] IRENA (2012) defines mini hydro power as plants with generating capacities between 100 to 1000 kW and small hydro power between 1 and to 10 MW.

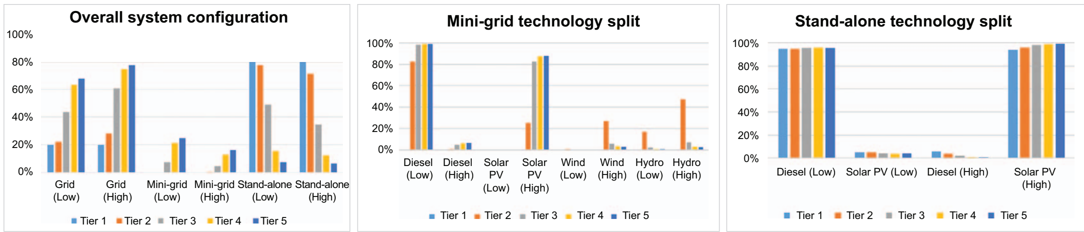

Figure 3. Overall system configuration (left); mini-grid technology choice (middle); stand-alone technology choice (right) for low and high diesel prices and for five tiers of electricity consumption.

with the information on annual mean water runoff[11] this results in a high resolution raster showing the average discharge values ($m^3 s^{-1}$). The global river network dataset was used to assign these discharge values to actual rivers. Each stream was assigned several attributes required for the estimation of hydro power potentials (elevation at sample and upstream point, distance to source, distance to mouth and several sample points located in a defined distance of 1 km from each other). Finally, the small and mini hydro power potentials were estimated with the hydropower equation [60, 61], based on the diversion (run-off-river) technique using impulsive turbine (e.g. Pelton) characteristics suitable for applications with high head and relatively low volume flow:

$$P_p = \rho * g * n_t * n_g * n_{ef} * \dot{Q}_{point} * (H_{p.up} - H_p)$$

where:
P_p: Potential power output at sample point in W
ρ: Water density constant (1000 kg m^{-3})
g: Gravitational constant (9.81 m s^{-2})
n_t: Turbine efficiency set as 0.88
n_g: Generator efficiency set as 0.96
$\dot{Q}_{point}$: Discharge flow at sample point in m s^{-3}
H_p: Elevation at sample point
$H_{p.up}$: Elevation at upstream point
n_{ef}: Conversion factor accounting for the environmental flow deduction (set as 0.6).

3. Results

Least-cost electrification options for 2030 were calculated and mapped for about 25.8 million locations in Sub-Saharan Africa and ten alternative scenarios (low and high diesel prices; five tiers of electrification). The electrification options—grid connections, mini grid and stand-alone solutions—vary from one scenario to another. This is summarised in figure 3.

[11] The map was made available at 0.5° spatial resolution by the European Joint Research Centre, therefore a resampling process was essential. This process yielded a raster layer showing the mean annual runoff stream flow (mm yr^{-1}) on a global scale at a spatial resolution of 0.00083°.

As household demand for electricity increases, the relative proportions of grid based and mini-grid solutions increase. This comes at the expense of stand-alone options. This is due to scale and operating cost considerations. At higher consumption levels, the proportionally higher quantum of fixed cost associated with the grid infrastructure of centralised (and mini-grid) power plants is divided by increasing generation volumes. The effect is to decrease the per unit cost of these systems. Supplying increasing volumes of electricity with stand-alone system, requires additional investments. Their cost per unit of generation would decrease slower than other systems.

The effect of operating costs vis-a-vis the diesel price is discussed with a focus on technology options.

The effects of increasing consumption on supply type split are well illustrated through maps associated with the low diesel price moving between Tiers 1, 3 and 5, illustrated below in figure 4. For reference, the existing and planned transmission infrastructure (lines larger than 69 kV) is also drawn on those maps. Note that for stand-alone systems the opacity is increased with increasing population figures. By population, for all tiers three to five grid-based connections dominate. This is simply as large areas of the continent are projected to be sparsely populated, making grid extension unviable while higher density urban settlements are already close to existing grids. Moving between Tiers 1 and 3, increases grid connection in relatively populous areas around Nigeria, Ethiopia and Lake Victoria. This becomes accentuated at Tier 5 electrification, with grid coverage over most of Western Africa.

Figure 4 (bottom right side) illustrates the interplay between diesel prices and the deployment of mini-grids, i.e. the share of mini-grid systems decreases with increasing diesel prices. The underlying dynamic is discussed next. Again, while mini-grids in the Tier 5 high-diesel scenario take up large areas, these are for relatively sparsely populated settlements.

Mini-grid technology deployment changes as a function of diesel price and electricity demand. Moving to higher tiers, mini-grid systems move from predominantly diesel to solar and hydro systems. This is particularly the case in the higher diesel price scenario. The relative transitions by tier and diesel price is given in figure 3 (middle).

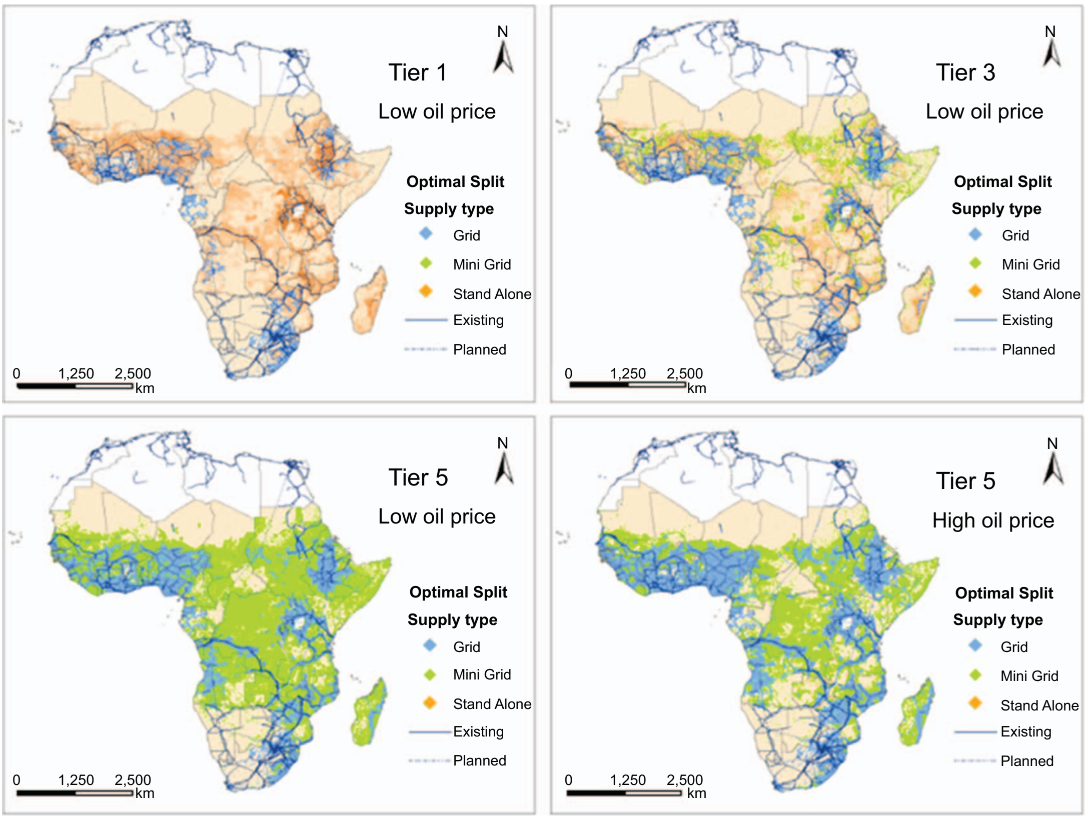

Figure 4. Least cost electrification mix for low diesel cost and Tier 1 (top left), 3 (top right) and 5 (bottom left); and high diesel cost and Tier 5 (bottom right).

As the diesel price increases, economies of scale effects decrease rapidly for gen-sets; from 25% market share (at low diesel price and Tier 5) to 1% (at higher diesel price and Tier 5). This is because their LCOE is dominated by fuel costs. As generation increases, so do fuel bills—while no fuel costs are incurred by solar, wind and hydro systems. There are however hefty quanta of infrastructure costs that are disproportionately large at low demand levels. As consumption increases, the per kWh costs decrease significantly and the diesel based mini-grids progressively gain market shares—from 0% (Tier 1) to about 1% (Tier 5).

In the case of stand-alone systems, the move from diesel to solar PV systems as a function of usage and diesel price is well illustrated in figure 3 (right hand side).

For reference, the numerical values of all splits are summarized in the appendix. Not only the access type but also the specific technologies are available on a spatial basis. In figure 5, the spatially explicit least-cost electrification technology is mapped for Tier 5—higher diesel price.

Population density and distribution play a significant role in the technology selection. This study utilizes a population dataset provided in a continuous raster format at approximately 1×1 km resolution (the highest publicly available continental resolution). It has been assumed that the population resides in the centre of the 1 km^2 block, as shown in the following schematic representation (figure 6). An alternative allocation of the population, say top left corner of the geographic block, was studied in Tanzania. This influenced the technology decision in ~0.13% of the studied locations within the country, implying minimal impact of the population allocation within a 1 × 1 km area.

3.1. Investment needs

The minimum total investment requirements to provide electricity the estimated 1.1 billion people in Sub-Saharan countries by 2030 amount to 50 billion US$ at low diesel prices and the lowest electrification level, while the maximum investment for universal access reach 1.3 trillion US$ at high diesel prices and the highest tier of electrification. Included are the capital costs for transmission and distribution infrastructure as well as for all off-grid systems (stand-alone and mini grid technologies). The investment costs for the grid generated electricity are obtained by The Electricity Model Base for Africa [43] based on the electricity generation mix of each country. A summary of the investment needs and the access split is shown in figure 7 and presented in detail in the appendix. The investment needs in the low diesel price scenario range from 50 to roughly 855 billion US$, whilst for the high diesel price the corresponding values stand at 64 billion US$ and 1.3 trillion US$, respectively. This occurs as higher diesel prices increase the system costs and improve the competitiveness of the relatively more expensive, (non-diesel based) grid and mini grid systems.

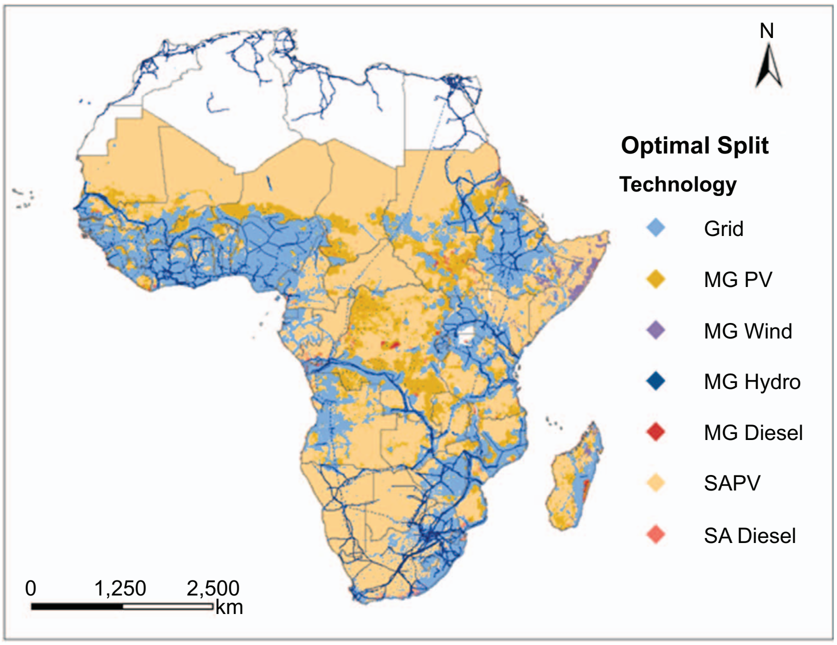

Figure 5. Least cost electrification technology for high diesel cost and Tier 5 (MG stands for Mini Grid systems and SA for Stand Alone).

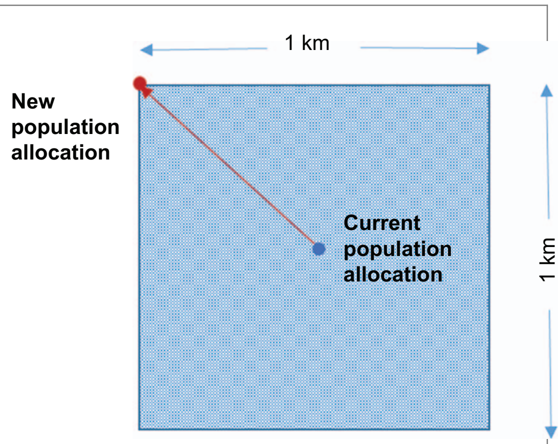

Figure 6. Population allocation in the centre and on the top left corner of a cell.

The significance of each access type in achieving full access to electricity by 2030 is illustrated by the cumulative investment curve per access type in figure 8 which considers the highest level of electricity demand (Tier 5). Access is provided to some 850 million people via grid expansion at an investment requirement of 900 billion USD; mini grid systems connect and supply around 180 million people at 260 billion USD. Stand-alone systems provide access to some 70 million people on the sub-continent at a cost of about 110 billion USD.

3.2. Implications for market development and assistance

The analysis and mapping suggest numerous policy implications. As data is separated by country, national level investment potentials are obtained. As technology categories and type are identified, information related to developing supply chains and maintenance might be gleaned. As technology is mapped to areas, there is the potential to define location specific concessions and support mechanisms. These might vary from national support to local and from market support or focus on engineering or resilience requirements where there are climate or other risks.

Taking advantage of this, assistance can be prioritised. For example, considering aid-related actions, by developing a simple index that divides the product of per-capita investment needs with country risk, divided by key considerations such as electricity access and use, other modern fuel access and institutional weakness simple rankings are possible. Applying a cursory index such as the Market Assistance Need Index (MANI), we find that Liberia, Democratic Republic of Congo, Somalia and Burundi rank highest in assistance need, while South Africa, Botswana and Namibia are countries that score very low on this index (for the cursory calculations, see the appendix).

For illustrative purposes, the LCOE and the MANI index are mapped and put next to each other in figure 9. On the left hand side, the LCOE (which includes fuel, investment and operation costs) increase from green to red. While on the right hand side, green indicates a low MANI and red higher. An immediate reflection is that areas with low LCOE and MANI may be spaces that the market, with limited intervention might be encouraged. While, on the other hand areas with high LCOE and MANI may need special assistance.

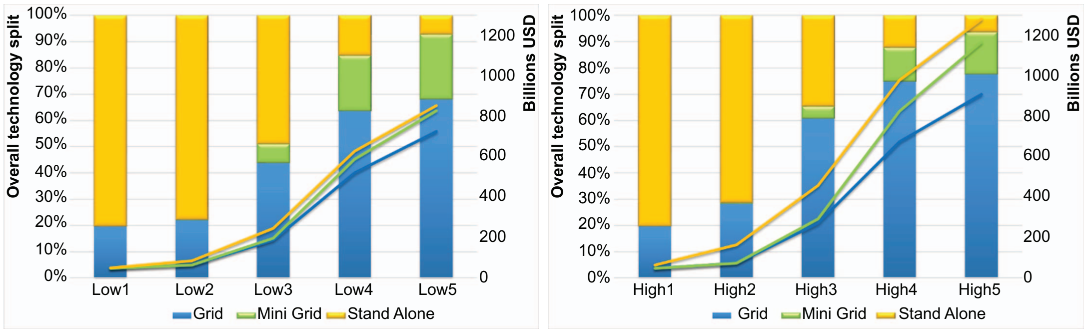

Figure 7. Access split for new connections, in bars, and overall investment needs, in lines, for universal access by 2030 for low diesel costs (left); and the same (right) for high diesel costs.

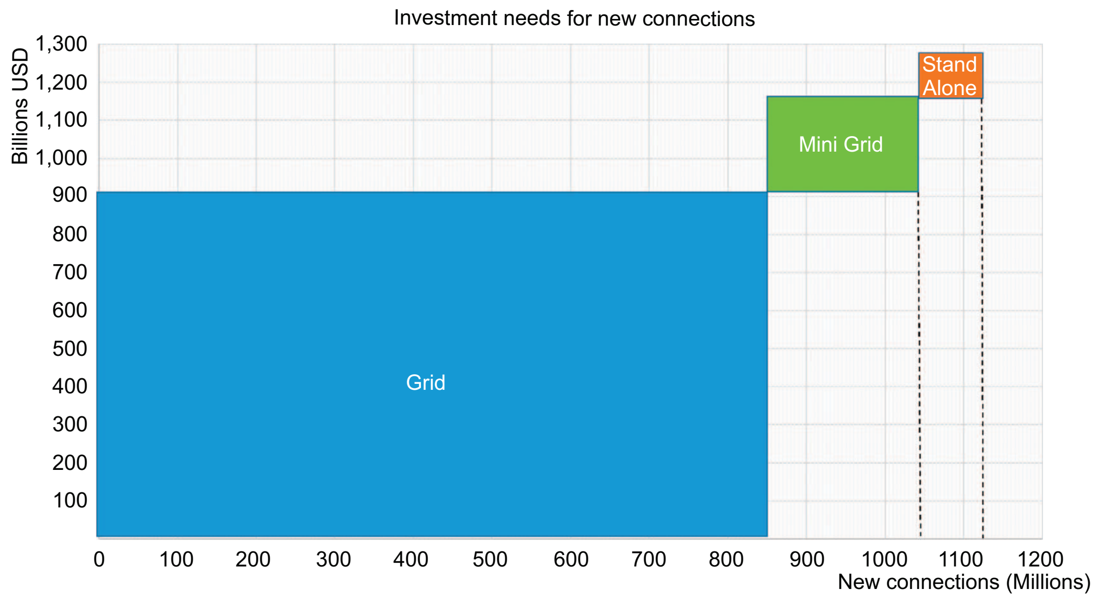

Figure 8. Cumulative investment curve per access type for new connections (high diesel costs, Tier 5).

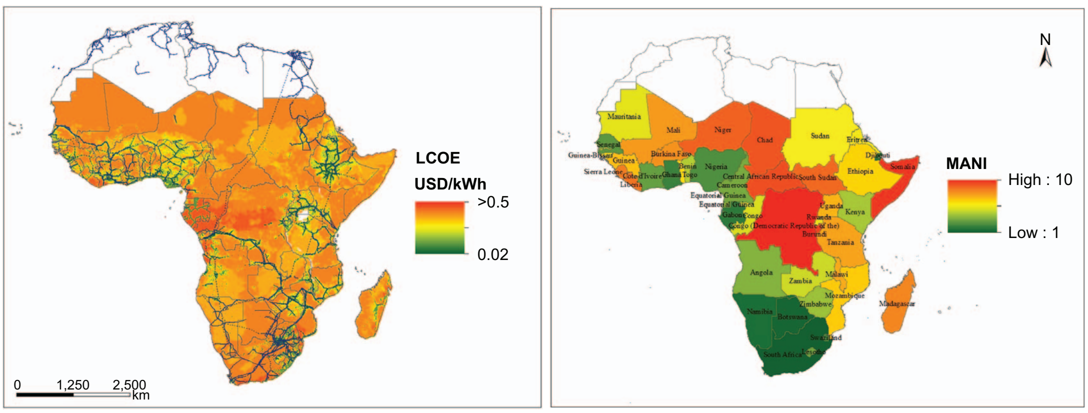

Figure 9. LCOE (left) and MANI for high diesel prices and Tier 5 (right).

4. Conclusions

Energy systems are inherently linked to geographic parameters, which are often inadequately considered in energy system models. The integration of GIS and energy system modelling helps identify the most effective electrification strategy on a geospatial basis. OnSSET is a complementary approach to existing energy planning models which do not consider geographical characteristics related to energy and allows analysts to improve upon the over-simplified dichotomy between on- and off-grid systems.

This study develops bottom up cost-optimal spatially explicit estimates of electrification technology mixes to meet different tiers of continental electricity access in Sub-Saharan Africa. It can be used to provide valuable support to policy makers on least-cost electrification strategies and to bridge science, technology and policy at different levels. Moreover, this tool can help planners and analysts identify investments by country, location and by technology type and support off grid electrification initiatives [62].

In low demand settings, decentralized generating options (solar, wind, hydro and diesel) contribute considerably to the achievement of universal access. As electricity demand increases, supply shifts to grid connections, i.e. centralized generation. As diesel prices increase there is a shift to greater deployment of renewable mini-grids, at the expense of diesel based stand alone and mini-grid systems.

The geospatial open-source electrification analysis presented in this paper lays the groundwork for exciting initiatives. In the policymaking arena, electrification planning is often captured by private consultants' analytical infrastructure. The open source and the modular structure of the presented tool allow for repeatable science, improvements in data and method to be incorporated. The tool can thus easily be transformed in an effective planning device for universal electrification strategies in countries and support the irreversible momentum of clean energy [63]. So much so that this effort forms the basis of United Nations [64] suite of tools to promote capacity development for achieving aspects of Sustainable Development Goal 7 (SDG7), such as access to affordable supplies of modern sustainable energy for all African countries. An effort to which contributions are welcomed.

While the analysis is a first of its kind in terms of scope, it provides the basis for an array of future analysis. This includes informing locally specific electrification support strategies. These might take cognisance of nationally specific levels of assistance required, or conceivably logistics planning.

The analysis can be improved in several ways. Available data might be improved with access to more up-to-date information, higher quality global data sets. Some of these might not be made available in the short term. However, therein lies interesting potential. For example, patterns associated with satellite night-light data might indicate more accurately the configuration of current HV, MV and LV power lines (revealed by 'continuous lines' of lights—likely interconnected to the same supply). The analysis itself might be more deeply nuanced. This might include heuristics to determine an electrification 'timeline' or prioritization, rather than a simple 'snapshot' of an ultimate access targets in 2030.

Table A1. Technologies compared for energy access

Category	Supply technology
Grid connection (Grid)	National grid
Mini grid systems (MG)	Solar PV
	Wind turbines
	Diesel generators
	Hydropower
Stand-alone systems (SA)	Solar PV
	Diesel generators

Further, only a limited number of scenarios are presented. These might be far from robust. Changes in population movement, technology change, transmission expansion plans, national and regional power pool development (as recently indicated [43]) may deeply affect costs and the 'optimal' technology choice. However, given the open nature of the experiment, answering these—and other—shortcomings might be a step closer than before.

Appendix: Methods

Cost calculations

Four parameters determine the LCOE per location assuming full electrification by 2030:

a. Target level and quality of energy access, i.e. the amount of electricity that already electrified and yet to be electrified households will be provided with, measured in kWh/household/year.

b. Population density, measured in households km^{-2}.

c. Local grid connection characteristics including the distance from the nearest grid (km) and the average national cost of grid supplied electricity $\$\,kWh^{-1}$.

d. Local renewable energy resource availability and diesel costs

The LCOE of a specific technology option represents the final cost of electricity required for the overall system to breakeven over the project lifetime. It is obtained with the following equation

$$\mathrm{LCOE} = \frac{\sum_{t=1}^{n} \frac{I_t + O\&M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \qquad (1)$$

where I_t is the investment expenditure for a specific technology option in year t, $O\&M_t$ are the operation and maintenance costs and F_t the fuel expenditures, E_t is the generated electricity, r the discount rate and n the lifetime of the option.

Note that the LCOE calculations for the mini grid and stand-alone electrification options reflect the total

Table A2. Electricity generation technology parameters used in the model. Sources: [65–68].

Plant type	Investment cost ($\$\,\mathrm{kW}^{-1}$)	O&M costs (% of investment cost/year)	Efficiency	Life (years)
Diesel Genset—Mini Grid	721	10%	33%	15
Mini and Small Hydro—Mini Grid	5000	2%	–	30
Solar PV—Mini Grid	4300	2%	–	20
Wind Turbines—Mini Grid	2500	2%	–	20
Diesel Genset—Stand Alone	938	10%	28%	10
Solar PV—Stand Alone	5500	2%	–	15

Table A3. Transmission and distribution costs in the model. Sources: [9], [43], [65], [69].

Parameter	Value	Unit
Life	30	Years
HV line cost (108 kV)	53000	USD km^{-1}
HV line cost (69 kV)	28000	USD km^{-1}
MV line cost (33 kV)	9000	USD km^{-1}
LV line cost (0.2 kV)	5000	USD km^{-1}
Tranformers	5000	USD/50 kVA
Additional connection cost per household connected to grid	125	USD/HH
Additional connection cost per household connected to mini grid	100	USD/HH
T&D losses	7%–29%	of capital cost/year
O&M costs of distribution	2%	of capital cost/year

Table A4. Other model parameters and assumptions. Sources: [43, 70].

Parameter	Value	Unit
National grid electricity cost (fuel cost)	0.02–0.16	USD kWh^{-1}
Discount rate	8%	–

system costs while the LCOE for the grid option is the sum of the average COE of the national grid plus the marginal LCOE of transmitting and distributing electricity from the national grid to the demand location. A detailed description of the model costs can be found in Nerini *et al* [9] and selected data is updated in tables A2–A4 above.

The cost analysis is carried out for the five different tiers of energy access outlined in the Global Tracking Framework Report [6].

Penalty cost assignment to electricity grid expansion processes

The expansion of the transmission network to areas lacking access is a capital intensive process. The investment costs are influenced by several factors such as the capacity, the type and the length of the lines as well as by the topology of the subjected area. In this analysis, a number of geospatial factors that affect the investment costs of the transmission network are identified and considered in order to assign an incremental capital cost in locations that indicate specific topological features. More particularly, investment cost is influenced by elevation, the road network, land cover type, slope gradient and distance from substations.

These datasets are classified to five categories and assigned a value between 1 and 5, 1 indicating the least and 5 the most suitable areas for grid expansion. The Analytic Hierarchy Process is used in order to quantify the importance (weight) of each geospatial factor in the additional investment cost associated with grid extension processes. The next step involves the combination of the re-classified layers along with their corresponding weight as to get a final combined layer applying a weighted overlay function in GIS environment. The classification and the weights of each geospatial dataset are stated in the table A5. The penalty cost can reach up to 30% of the initial investment cost.

Household size

The household size is an important parameter in the electrification planning analysis as it affects the connection costs per household. These are calculated based on (a) the projected mean national household size values [71] (b) the existing and projected national, urban and rural populations [72] (c) the urban to rural household size ratio given in demographics and health country surveys (see table A6). For the countries where urban and rural household sizes are given, we calculate the weighted mean household size knowing the corresponding populations. The known urban and rural household sizes are used to estimate the urban to rural household size ratio per power pool. For the countries where only the mean national household size is known, we use the above mentioned ratio and the urban/rural populations to estimate the urban/rural household size.

Table A5. Classification and weights of each geospatial dataset.

Geospatial factor	Weight	Class A	Class B	Class C	Class D	Class E
Digital elevation (m)	15%	0–500	501–1000	1001–2000	2001–3000	>3000
Distance to roads (km)	5%	0–5	5.1–10	10.1–25	25.1–50	>50
Slope (degrees)	32%	0–10	10.1–20	20.1–30	30.1–40	>40
Distance to sub-stations (km)	9%	0–0.5	0.6–1	1.1–5	5.1–10	>10
Land cover[a]	39%	7,9,10,14,16	2,4	1,3,5,12,13,15	6,8	0,11
Suitability index	100%	5	4	3	2	1

[a] Further clarification can be found at http://glcf.umd.edu/data/lc/.

Wind energy potentials

GIS data of global mean annual wind speeds at 50 m height and 5 km spatial resolution were obtained by the Global Wind Atlas [73] based on ten years of hourly data and validated against ground measurements. These data are used to calculate the capacity factor [74]. The latter is defined as the ratio of the yearly expected wind energy production to the energy production if the wind turbine were to operate at its rated power throughout the year. The capacity factor reflects the potential wind power at a given site and it can be used for comparing different sites before the installation of wind power plants. The spatial distribution of wind power capacity factors for areas where it is technically feasible to install wind farms is presented in figure A1. This is translated to a cost and used as an input to the model for the mini-grid options based on the parametric analysis shown in [9].

Solar energy potentials

The global solar data set was obtained from the Global Solar Atlas [75]. This provides average annual global horizontal irradiation (GHI) (kWh m day^{-2}) at 3 km resolution. The data is based on over ten years of hourly data derived from satellite imagery and validated against ground measurements. Applying standard geospatial analysis, the irradiance data were further processed to yield to the annual irradiance for each grid cell (kWh m yr^{-2}).

The LCOE of stand-alone solar PVs is calculated based on the radiation and the system costs as presented in [8]. An illustration of the global horizontal irradiance map is illustrated in figure A2. The LCOE of mini-grid solar PVs is calculated based on the above parameters and the population density of settlements.

Spatial LCOE generated by diesel

To calculate the LCOE of diesel generators, the international diesel price (current and projected), the travel distance from major cities to each grid point, global coastlines and the characterization of a country as landlocked or coastal are considered. The current oil price is 47 US$/bbl [53], while the projected one reaches 113 US$/bbl according to the IEA New Policies Scenario [54]. There are no subsidies or taxes taken into account in this analysis.

Table A6. Household size in Sub-Saharan African countries in 2030.

Country	Mean national household size	Mean urban household size	Mean rural household size
Angola	6.1	5.6	6.7
Botswana	1.9	1.7	2.1
Benin	3.3	3.1	3.6
Burkina Faso	4.8	4.4	5.1
Burundi	4.0	3.5	4.1
Cameroon	3.1	3.0	3.3
Central African Republic	5.3	5.0	5.6
Chad	5.5	5.1	5.6
Congo	3.6	3.5	3.9
Congo, DR	4.7	4.4	4.9
Côte d'Ivoire	5.0	4.7	5.5
Djibouti	6.8	6.5	7.7
Equatorial Guinea	5.5	5.2	5.7
Eritrea	5.1	4.5	5.4
Ethiopia	5.0	4.4	5.2
The Gambia	6.9	6.6	7.6
Gabon	4.0	4.0	4.4
Ghana	3.5	3.3	3.8
Guinea	6.1	5.6	6.5
Guinea-Bissau	5.3	5.0	5.8
Kenya	3.3	3.0	3.5
Liberia	5.0	4.6	5.4
Lesotho	2.9	2.6	3.1
Madagascar	4.1	3.7	4.4
Malawi	4.0	3.5	4.1
Mali	5.9	5.4	6.3
Mauritania	6.4	6.1	7.0
Mozambique	4.1	3.7	4.4
Namibia	3.1	2.9	3.4
Niger	6.4	5.7	6.6
Nigeria	4.3	4.0	4.6
Rwanda	5.2	4.7	5.6
South Africa	2.4	2.3	2.7
Senegal	7.8	7.2	8.4
Sierra Leone	4.8	4.4	5.2
Somalia	6.1	5.6	6.6
South Sudan	6.5	5.7	6.8
Sudan	6.2	5.5	6.5
Swaziland	2.5	2.2	2.6
Togo	3.6	3.3	3.8
Tanzania	4.3	3.9	4.6
Uganda	3.9	3.4	4.0
Zambia	4.9	4.5	5.3
Zimbabwe	4.1	3.7	4.3

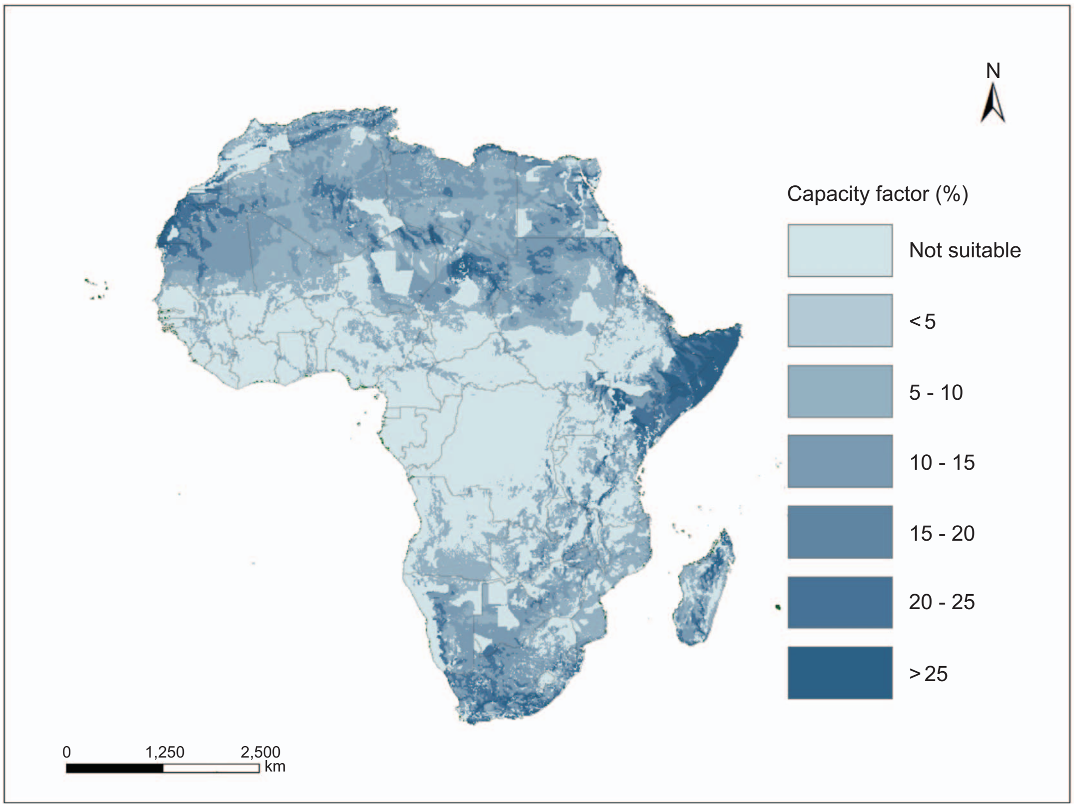

Figure A1. Wind power capacity factor after geographic restrictions.

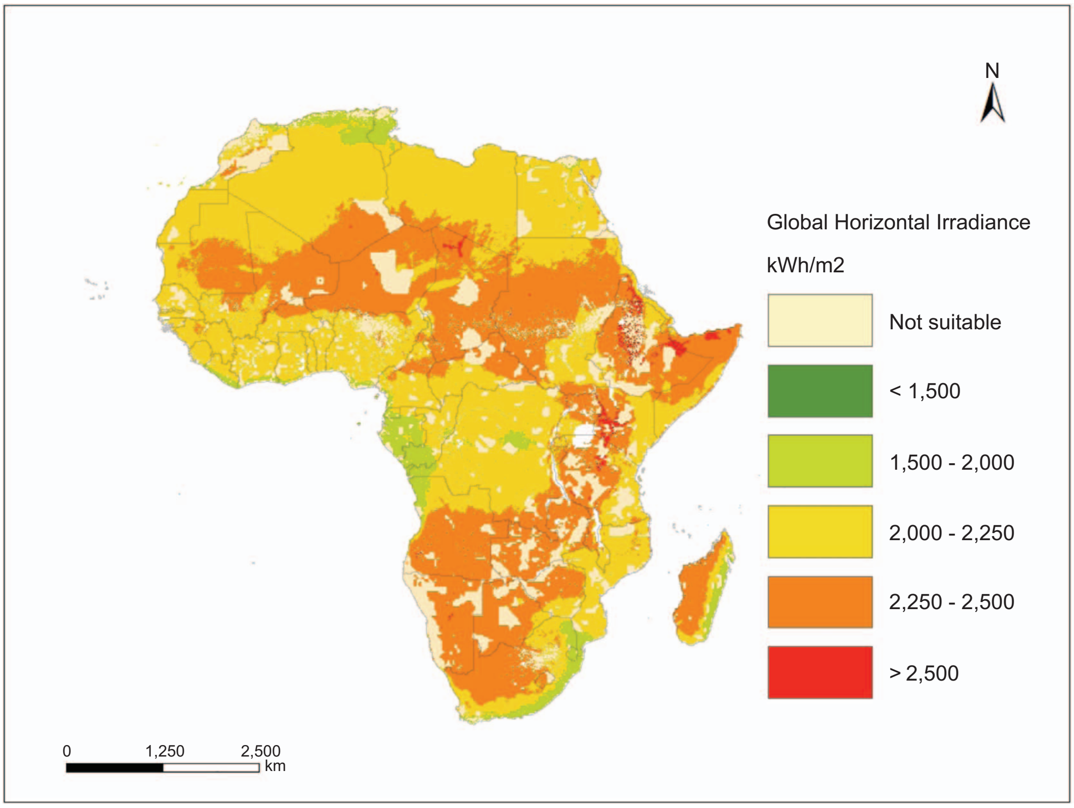

Figure A2. Global horizontal irradiance after geographic restrictions for mini grid and stand-alone applications.

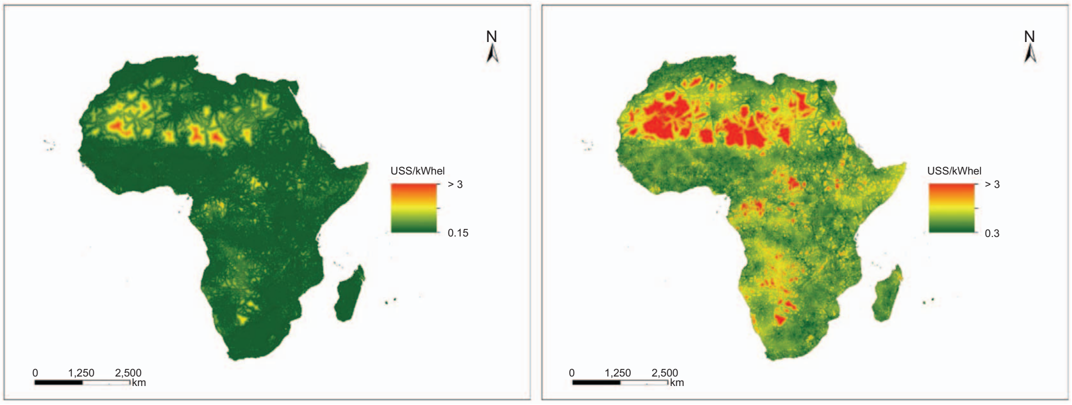

Figure A3. Levelized cost of electricity for diesel generation (current diesel price on the left, New Policies Scenario 2030 projected diesel price on the right).

Table A7. Summary of the technology split for the African continent (percentages of new connections).

Scenario/Electrification option	Technology split Grid	Mini Grid	Stand Alone	Stand alone Diesel	Solar PV	Mini Grid Diesel	Solar PV	Wind	Hydro
Low 1	20%	0%	80%	95%	5%	0%	0%	0%	0%
Low 2	22%	0%	78%	95%	5%	83%	0%	1%	17%
Low 3	44%	7%	49%	96%	4%	98%	0%	0%	2%
Low 4	64%	21%	15%	96%	4%	99%	0%	0%	1%
Low 5	68%	25%	7%	96%	4%	99%	0%	0%	1%
High 1	20%	0%	80%	6%	94%	0%	0%	0%	0%
High 2	28%	0%	71%	4%	96%	1%	25%	27%	47%
High 3	61%	5%	35%	2%	98%	5%	83%	6%	7%
High 4	75%	13%	12%	1%	99%	6%	88%	3%	3%
High 5	78%	16%	6%	1%	99%	7%	88%	3%	2%

The calculation of the diesel costs varies from coastal to landlocked countries as described below.

For coastal countries

The price in the major cities of countries with coastal access is equal to international price on the coast with one uniform price on all coastlines. In remote areas the transport cost is enumerated taking into account the diesel price on the coast, the diesel consumption of a truck, the volume of the truck and the transportation time.

Then, the electricity generation cost is calculated considering the conversion efficiency of a diesel generator. Finally, the LCOE is calculated by adding labour, maintenance and amortization costs.

For landlocked countries

The diesel price in major cities of landlocked countries is determined by adding transportation costs from the coast to the international price of the closest coastline. For remote areas diesel costs are calculated similarly to the remote areas in coastal countries.

Transport cost P_t *(\$ kWh_{th}^{-1})*

$$P_t = 2 * \frac{P_d * c * t}{V} * \frac{1}{LHV_d} \quad (1)$$

where P_d is the international market price of diesel (\$ l^{-1}), c the diesel consumption ($l\,h^{-1}$), t is the transport time (h), V the volume of diesel transported (l) and LHV_d is the lower heating value of diesel ($kWh\,l^{-1}$).

Electricity production cost P_p *(\$ kWh_{el}^{-1})*

$$P_p = \left(\frac{P_d}{LHV_d} + P_t\right)/\eta + P_{O\&M} \quad (2)$$

where η is the electrical efficiency of the diesel generator (kWh_{el}/kWh_{th}) and $P_{O\&M}$ the labour, maintenance and amortization costs.

Taking into account the above, the total cost of electricity produced by diesel generators is given by the following formula:

$$P_p = (P_d + 2 * \frac{P_d * c * t}{V}) * \frac{1}{\eta * LHV_d} + P_{O\&M} \quad (3)$$

Figure A3 shows the spatial variance of the electricity costs per kWh delivered by a diesel generator for both the current and the projected oil price for stand-alone systems. For mini grid systems, the electrification model calculates the LCOE considering additionally the population density of settlements.

Table A8. Investment needs for universal access by 2030, in billion USD.

Country	Low 1	Low 2	Low 3	Low 4	Low 5	High 1	High 2	High 3	High 4	High 5
1. **Angola**	1.55	2.58	6.87	17.11	22.65	1.86	4.33	11.98	26.02	33.90
2. **Benin**	0.57	0.91	2.45	6.60	9.22	0.70	1.74	4.67	10.00	12.97
3. **Botswana**	0.32	0.40	0.65	1.34	1.77	0.33	0.50	1.01	2.05	2.69
4. **Burkina Faso**	0.32	1.02	3.21	11.45	16.53	0.72	2.94	9.54	22.52	29.30
5. **Burundi**	0.15	0.47	4.41	10.78	14.34	0.42	2.05	6.08	12.08	15.80
6. **Cameroon**	1.96	2.99	6.49	16.95	23.93	2.16	4.19	10.88	24.18	32.23
7. **Central African Republic**	0.07	0.23	0.76	1.92	2.69	0.16	0.73	2.50	6.24	8.69
8. **Chad**	0.18	0.69	2.62	6.89	9.59	0.51	2.50	8.52	21.04	29.06
9. **Democratic Republic of the Congo**	1.63	5.03	19.24	53.27	74.15	3.14	13.74	45.98	110.00	148.47
10. **Djibouti**	0.03	0.05	0.12	0.30	0.43	0.04	0.09	0.25	0.58	0.78
11. **Equatorial Guinea**	0.16	0.21	0.37	0.73	0.98	0.17	0.25	0.51	1.01	1.51
12. **Eritrea**	0.28	0.52	1.26	3.09	4.53	0.34	0.86	2.55	6.23	8.25
13. **Ethiopia**	3.70	8.32	30.56	72.58	95.22	4.81	14.45	44.29	88.59	114.53
14. **Gabon**	0.42	0.55	0.92	1.75	2.30	0.43	0.58	1.05	2.09	2.78
15. **Gambia**	0.05	0.11	0.38	0.95	1.27	0.08	0.28	0.84	1.75	2.31
16. **Ghana**	2.21	3.09	6.82	15.59	21.09	2.39	4.15	9.31	18.45	23.92
17. **Guinea**	0.32	0.69	2.30	6.86	9.61	0.54	1.84	5.52	11.42	14.72
18. **Guinea-Bissau**	0.16	0.22	0.43	0.95	1.27	0.18	0.31	0.73	1.60	2.05
19. **Ivory Coast**	1.64	2.32	4.58	12.75	17.61	1.83	3.36	8.90	17.99	22.71
20. **Kenya**	1.71	3.44	15.48	44.69	60.97	2.44	7.60	24.64	52.61	69.93
21. **Lesotho**	0.11	0.19	0.47	1.32	1.81	0.13	0.32	0.94	2.10	2.66
22. **Liberia**	0.06	0.21	0.71	2.21	3.08	0.13	0.63	2.09	4.58	5.83
23. **Madagascar**	0.52	1.18	4.15	12.71	17.94	0.98	3.81	12.57	27.38	35.65
24. **Malawi**	0.29	0.75	5.03	11.98	15.28	0.69	3.03	8.89	16.44	20.88
25. **Mali**	0.52	1.03	3.15	9.33	13.29	0.84	2.85	8.88	20.01	26.33
26. **Mauritania**	0.10	0.26	0.77	2.13	2.93	0.17	0.63	2.11	5.27	7.19
27. **Mozambique**	0.77	1.68	5.33	18.29	26.20	1.28	4.60	15.00	34.63	45.04
28. **Namibia**	0.22	0.32	0.69	1.50	1.95	0.24	0.41	0.95	2.01	2.59
29. **Niger**	0.38	1.24	4.55	13.77	19.23	0.87	3.77	12.21	28.26	37.24
30. **Nigeria**	11.71	16.98	38.10	93.57	127.35	13.27	25.97	61.65	120.06	153.05
31. **Republic of Congo**	0.24	0.52	1.78	4.49	6.47	0.27	0.87	2.54	6.33	8.64
32. **Rwanda**	0.28	0.58	1.83	3.65	4.70	0.49	1.79	4.01	7.69	10.05
33. **Senegal**	0.85	1.39	3.24	9.07	12.44	1.00	2.26	6.21	12.90	16.67
34. **Sierra Leone**	0.09	0.24	0.95	2.91	4.24	0.18	0.85	2.79	6.14	7.78
35. **Somalia**	0.32	0.77	2.20	4.86	6.52	0.48	1.61	4.61	10.63	14.41
36. **South Africa**	10.73	12.59	18.28	31.77	40.88	10.86	13.32	20.91	37.96	48.69
37. **South Sudan**	0.14	0.58	2.12	5.51	7.46	0.40	2.06	7.21	17.80	23.46
38. **Sudan**	1.26	2.66	8.19	20.03	27.97	1.84	5.80	17.18	40.36	55.10
39. **Swaziland**	0.15	0.18	0.28	0.77	1.10	0.16	0.26	0.60	1.18	1.43
40. **Tanzania**	1.22	2.90	11.72	35.82	49.75	2.24	8.87	28.17	61.34	80.51
41. **Togo**	0.30	0.53	1.44	3.89	5.57	0.40	1.11	3.23	6.90	8.86
42. **Uganda**	1.21	2.39	13.41	31.92	41.75	2.01	7.03	19.47	36.80	46.98
43. **Zambia**	0.46	1.23	3.71	9.43	12.85	0.73	2.58	7.94	18.87	25.56
44. **Zimbabwe**	0.98	1.40	2.78	9.21	13.66	1.19	2.61	7.36	16.62	21.28
TOTAL	50.32	85.64	244.78	626.68	854.55	64.09	163.50	457.26	978.67	1282.48

Technology market share by category and type

A simple market assistance index

MANI is defined as shown in the following formula whereas the indicators are normalized and adjusted to a 1–10 non-dimensional scale where 1 represents the worst performance and 10 the optimal:

$$MANI = \frac{Investment\ needs\ per\ capita\ index * Country\ risk}{Access\ to\ electricity * El.\ consumption\ per\ capita\ index * Access\ to\ modern\ fuels\ index * Institutional\ Weakness\ index}$$

- Investments needs per capita index refers to the total investment requirements per capita for universal access.
- Institutional weakness index of state weakness in the developing world ranks the countries according to their relative performance in four spheres: economic, political, security, and social welfare. A weak state is defined as a country that lacks access to the essential capacity and/or will to fulfil four sets of government responsibilities: establishing and maintaining legitimate, transparent, and accountable political institutions (good governance); fostering an environment conducive to sustainable and equitable economic growth; securing their populations from violent conflict and controlling their territory; and meeting the basic human needs of their population, where (a lower index indicates 'weaker' countries) [76].
- Country risk refers to the risk of non-payment by companies in a given country. This indicator informs potential investors in making informed decisions about the potential risks of their business activity in a country [77].
- Access to electricity [2], electricity consumption per capita [78] and access to modern fuels are defining factors of energy poverty. Access to modern fuels is calculated using the percentage of the population that relies on solid fuels as the primary source of domestic energy for cooking and heating [79].

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