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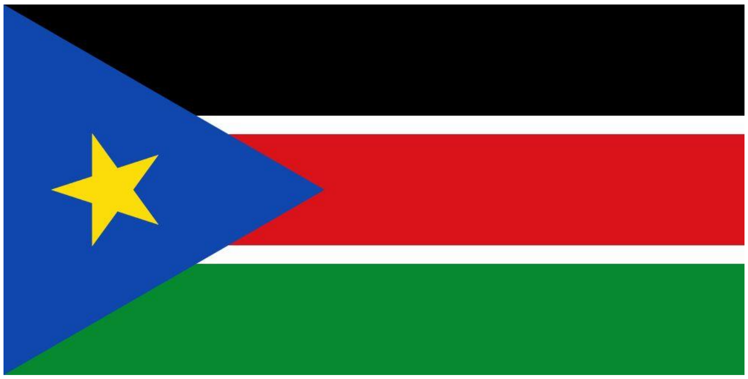

HIGH-LEVEL LEAST-COST ELECTRIFICATION PROSPECTUS

For achieving 50% electrification access target by 2030

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Geospatial Electrification Planning in the Africa Region (GEPAR)

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1 Executive Summary

1. **South Sudan, a landlocked country in East Africa with a population of over 11 million, has experienced significant levels of fragility, conflict, and violence.** At independence in 2011, South Sudan's economy and infrastructure had been devastated by decades of instability and conflict with Sudan. Human development indicators placed the country among the poorest in Africa. The outbreak and continuation of violence since December 2013 have further eroded South Sudan's development potential, worsened the humanitarian situation, and deepened vulnerabilities. From August 2019 to April 2020, about 6.35 million people suffered from crisis or acute food insecurity, making South Sudan one of the most food-insecure countries globally. This has been exacerbated by floods in 2019 which affected 900,000 people and caused wide-spread displacement and destruction. The COVID-19 pandemic, adverse weather shocks, and locust infestations have further intensified an already challenging situation.

2. **The country faces a large deficit in electricity access, especially in rural areas.** According to data from 2021 SE4ALL Global Tracking Framework, about 7% of total population in South Sudan has access to electricity (13%Urban and 5% Rural). Off-grid solutions, such as solar home systems and mini-grids, could complement grid expansion and help accelerate rapid expansion of electricity access in South Sudan in a cost-effective manner. However, public capacity to procure these technologies is limited and the private off-grid sector is still in its infancy.

3. **As the first step to address the huge access deficit in South Sudan, the World Bank provided technical assistance to South Sudan to identify the least-cost electrification option(s) using the GIS Open-Source Spatial Electrification Tool (OnSSET).** OnSSET is a GIS[1] based tool that helps to identify the least-cost electrification option(s) between three alternative access modalities:

- Grid connection/extension
- Mini grid systems (Solar PV, Wind Turbines, Diesel gensets, Small scale hydropower)
- Stand-alone systems (Solar PV, Diesel gensets)

4. The open-source geospatial electrification toolkit was developed by the division of Energy Systems Analysis at KTH Royal Institute of Technology in partnership with United Nations, World Bank, International Energy Agency, ABB, Swedish International Development Agency, among others. OnSSET takes the existing and planned transmission and distribution network (down to 33kV lines) as given and optimizes technological solutions to electrification in a cost-effective manner to meet service requirements.

5. **The analysis shows that accelerating electricity access expansion requires high levels of investment.** Although there is no official national electrification target, the model sets a modest target of 50 percent of electrification rate by 2030.[2] Achieving 25 percent by 2025 will require connecting 600,000 people per year, accounting for population growth. Achieving 50 percent access by 2030 requires connecting ~1 million people per year between 2026 and 2030. In total, around 3.7 million people will gain access to electricity by 2025 and around 8.9 million people by 2030.

6. **To achieve 50% electricity access by 2030, South Sudan will require US$500 million to US$1,920 million of investment,** depending on the household energy demand and the cost of grid-connection generation expansion. Due to lack of reliable data and methods, the analysis developed two assumptions

[1] Geographic Information Systems

[2] Although the SDG7 target is universal access by 2030, it is unrealistic for South Sudan given that current rate is only 7 percent.

for household energy demand and grid costs based on regional and global baselines, and thus established four scenarios. These are: i) low demand (urban Tier 4 Rural Tier 2) and low grid cost (US$0.1/kWh), ii) low demand and high grid cost (US$0.37/kWh), iii) High demand (Urban Tier 5 Rural Tier 3) and low grid cost, and iv) high demand and high grid cost. These four scenarios attempt to capture potential least-cost electrification solutions based on assumptions of future economic and social development.

7. **Off-grid solutions and mini-grids will be dominant in the effort to achieve a higher electrification rate in South Sudan if the cost of grid generation remains high and there is no expansion of the national transmission and distribution backbone network.** The current cost of grid generation from existing sources is around US$0.37/kWh[3], one of the highest in the region, and thus in the absence of significant reductions in generation costs solar home systems and mini-grids are likely to be the least-cost option for most new connections. If, however, as a result of extensive near-term investments in hydropower and other lost-cost energy sources, the cost of grid came down to an average of about US$0.10 cents/kWh (in line with more mature power sectors in the region) grid electricity could be the least-cost connection option for almost half of the 50 percent access target.

8. **As a next step, a comprehensive least-cost generation and tarnsmission system planning exercise accompanied by a detailed GIS analysis is needed to help the Government of South Sudan to refine the analysis and set robust electrification targets and policy.** This high-level analysis has several major limitations. For one the model only takes into account existing and already planned grid infrastructure, and is not able to itself recommend new investments in transmission lines. As South Sudan currently lacks both a national grid and a transmission master plan, the model does not take a view on transmission expansion. For another, current access rates are based on night-time light satellite data, the granularity of which is limited by the amount of light that can be picked up from space. The model does also not consider industrial or commercial demand, and even for household demand it relies on high-level assumptions and extrapolations in the absence of more detailed data. Finally, the fact that South Sudan's "grid" is really more of a series of isolated mini-grids presents some classification challenges that might lead to a slight overestimation of investment costs.

2 High-level Analysis for Least-Cost Electrification

9. This high-level analysis study conducted by the World Bank is based on the Global Electrification Platform (GEP) OnSSET model[4], which identifies the least-cost electrification option(s) between three technological solutions involving seven alternative configurations; grid connection/extension, mini grid systems (solar PV, wind turbines, diesel gensets, small scale hydropower), and stand-alone systems (solar PV, diesel gensets). The model was developed by the division of Energy Systems Analysis at KTH Royal Institute of Technology in partnership with United Nations, World Bank, International Energy Agency, ABB, and Swedish International Development Agency, among others. The GEP-OnSSET model combines geospatial information related to infrastructure, resources, topology and socio-economic characteristics over a modelled area, in order to inform a tree search algorithm. The algorithm traverses iteratively through a sub-set of un-electrified population settlements to identify the nearest neighbor and optimal electrification technology. Results indicate the optimal technology mix, capacity and investment requirements for achieving electricity access goals under pre-defined time series (which may include multiple time steps; minimum duration of a time step is one year).

[3] Grid supply cost is based on the cost of service in Juba, which has an isolated grid with 33MW of operational generation capacity
[4] Open source code for the GEP OnSSET model is available via GitHub at https://github.com/global-electrification-platform/gep-onsset and the previous old results of scenarios for Sub-Saharan countries including South Sudan using the same model with generic assumptions are available at https://electrifynow.energydata.info/explore/ss-1

2.1 GEP Model Specifications

10. **For South Sudan, the GEP model was used to conduct a high-level analysis to determine the least-cost technology mix to achieve electricity access target rates of 25% by 2025 and 50% by 2030.** Based on the GEP-OnSSET model, updated results for South Sudan have been generated using refined data gathered and provided by the World Bank's South Sudan energy team. The following table provides key data inputs and assumptions that feed into the GEP model as non-spatial parameters, such as current demographics and status of electrification in South Sudan:

Table 1: Key non-GIS Assumptions

Key non-GIS assumptions	Data	Sources
Population Start year (2020) [million]	13.3	NDS (2020)
Population End year (2030) [million]	17.9	United Nations | DESA Population Division,2019
Urbanization rate Start year (2020) [%]	17	NDS (2020)
Urbanization rate End year (2030) [%]	24	NDS (2020)
Household size (urban)	7.1	S. Sudan National Bureau of Statistics (2009)
Household size (rural)	6.4	S. Sudan National Bureau of Statistics (2009)
Electrification rate 2020 (grid) [%]	7.0%	Tracking SDG7 2021, World Bank
Electrification rate 2020 (urban) [%]	13.0%	Tracking SDG7 2021, World Bank
Electrification rate 2020 (rural) [%]	5.0%	Tracking SDG7 2021, World Bank
Electrification target 2025	25%	Energy team estimate
Electrification target 2030	50%	Energy team estimate
Grid generation cost [USD/kWh]	0.10/0.37	Energy team estimate
Grid power plants capital cost [USD/kW]	1183	Estimates based on Literature[5]

11. **As noted, the GEP model is a bottom-up, geospatial electrification model used to estimate least-cost solutions for each settlement in the country.** The following five key analytical steps of the model were used to conduct this high-level analysis for South Sudan:

Step 1. All households in the country are clustered into settlements of varying sizes based on spatial patterns of households using publicly available geospatial population data (e.g.: the high-resolution settlement layer -HRSL).[6] Some clusters are small in size but densely populated typically in urban and some clusters in rural areas are larger in size with more dispersed households.

Step 2. Each settlement is then classified as rural or urban based on national statistics, which forms the basis for a demand estimate for that settlement. Households within rural

[5] I. Pappis, "Electrified Africa – Associated investments and costs," 2016

[6] Facebook Connectivity Lab and Center for International Earth Science Information Network. High Resolution Settlement Layer available via https://data.humdata.org/organization/facebook

settlements are assumed to have a different demand than households within urban settlements.

Step 3. Each settlement is also classified as either ‘with electricity access’ or ‘without electricity access’ based on nighttime satellite imagery and other data as proxy. See the Annex for details on this methodology.

Step 4. Each settlement is also classified as either ‘with electricity access’ or ‘without electricity access’ based on a GIS-based multi-criteria evaluation,[7] including distance to service transformers, Medium-voltage (MV) and High-voltage (HV) lines; Night-time Light (NTL) intensity; and population size if data is available.

Step 5. For each unelectrified settlement, the model then determines the least-cost electrification solution for 2025 and 2030 based on (i) settlement-level electricity and access data (e.g. estimates of demand, distance to the grid, renewable energy potential); (ii) country-level electrification targets for 2025 and 2030; (iii) country-level assumptions about the costs of different electricity access solutions; and (iv) general country-level population trends and other economic assumptions (all non-spatial input assumptions are included in the Annex).

12. **The electrification analysis with the GEP model is based on information collected by a number of GIS layers. These are used to provide all necessary, initial attributes that the model needs to run.** A basic analysis relies on the following “fundamental” GIS layers whose data availability for South Sudan is indicated:

- Distribution of HV lines (current & planned): Spatial distribution (current & planned) of the transmission network. HV capacity definition depends on the country but usually refers to lines above 69 kV. South Sudan does not have an existing national transmission network. The analysis incorporated two scenarios with or without planned transmission network. The planned transmission network was downloaded from http://africagrid.energydata.info/. However, this plan is indicative and is not based on a formal planning exercise.

- Distribution of MV lines: Spatial distribution of the medium voltage transmission network. What is defined as medium voltage depends on the country but usually refers to lines between 11–69 kV. South Sudan has isolated distribution networks in Juba and a few other cities at a small scale. Data on existing distribution networks was sourced from SSEC.

- Location of Substations: The location of currently available substations. Capacity and type should be provided as attributes. Data was not provided for South Sudan.

- Transformers: The location of currently available transformers. Capacity and type should be provided as attributes. Data is available for South Sudan but was not provided in a GIS compatible format and hence not usable.

[7] The GIS-based multi-criteria evaluation to determine electricity access status for each settlement is based on distance to service transformers, distance to MV lines, distance to HV lines, Nigh-time light (NTL) intensity, and population size which are provided as input assumptions to the model. The specific values are provided below in the section “Methodology to Determine Access Status of Settlements”

- Road network: Existing & planned road infrastructure. Detail should go as low on the road scale as can accommodate a pickup/truck. Data for South Sudan is publicly available and downloaded from https://www.mapzen.com/blog/osmlr-2nd-technical-preview/.

- Global Horizontal Irradiation (Solar): Global Horizontal Irradiation(kWh/m2/year) over a given area. Data for South Sudan was extracted from the global scale dataset which is publicly available from https://globalsolaratlas.info/downloads

- Wind speed: Wind velocity (m/sec) in a given area. This layer may be substituted by wind power density maps (W/m2). Data for South Sudan was extracted from the global scale dataset which is publicly available from https://globalwindatlas.info/downloads

- Location of Small Hydropower potential sites: Points of potential of mini/small hydropower potential. The layer should include information regarding the location of potential sites, power output (kW), head (m), and discharge (m3/year). Data for South Sudan was not provided.

- Land Cover: Raster land cover classification. Data for South Sudan was extracted from the global scale dataset which is publicly available from http://glcf.umd.edu/data/lc/

- Elevation & Slope: Raster filled Digital Elevation Model (DEM) maps. Data for South Sudan was extracted from the global scale dataset which is publicly available from http://www.cgiar-csi.org/data

- Administrative boundaries: Basic geographic information (e.g., name) for the country(s) to be modelled and delineation of the boundaries of the analysis. Data for South Sudan is publicly available from https://gadm.org/download_country_v3.html

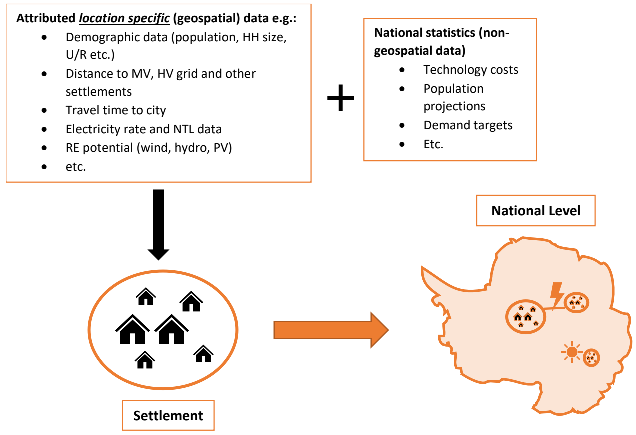
- Population distribution: Spatial quantification of the population for a selected area of interest (usually country or continent). Data for South Sudan is publicly available from 2018 from https://www.ciesin.columbia.edu/data/hrsl/

- Travel time to nearest town: Visualizes spatially the travel time required to reach from any individual cell to the closest urban center. Data for South Sudan was extracted from the global scale dataset which is publicly available from https://map.ox.ac.uk/research-project/accessibility_to_cities/

- Nighttime lights: Night-time light maps showing light pollution. The map has a relative scale for the intensity of light. Data for South Sudan was extracted from the global scale dataset which is publicly available from https://ngdc.noaa.gov/eog/viirs/download_dnb_composites.html

13. The basis of an electrification analysis with GEP OnSSET model is the geo-location of population or settlements. Distribution of population might be available as a raster layer (e.g. HRSL from Columbia/Facebook) or as vector layer (SEDAC).

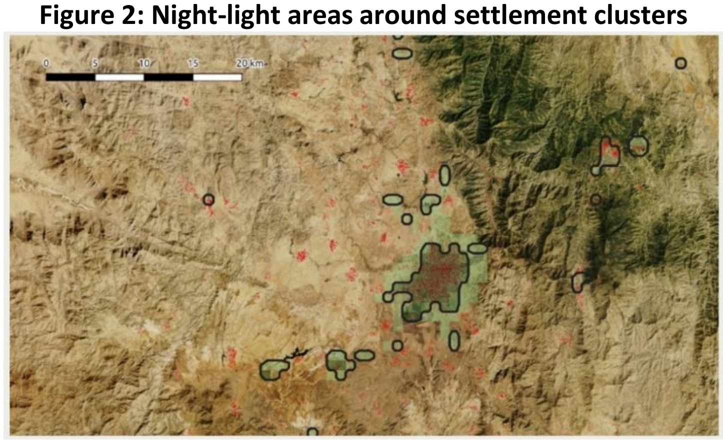
Figure 1: Bottom-up Methodology of the Electrification Model



2.2 Methodology to Determine Access Status of Settlements

14. **The energy access model used in this GEP model relies on SDG7 tracking framework report on the updated access rate and satellite images to determine the spatial distribution of electrification of settlements.** According to the 2021 SE4ALL Global Tracking Framework, about 7% of total population in South Sudan has access to electricity (13% Urban and 5% Rural). The analysis uses this as baseline for the country's electrification rate. Night-time light maps capture anthropogenic light sources on the surface of the earth using satellite imagery. Non-human sources of light, such as lunar reflections and fires, are removed, producing satellite data with compelling images of urbanization and access to electricity. This is a good proxy for assessing where electrified human settlements are, as these tend to give light pollution. In the GEP OnSSET model these nighttime light maps are used to estimate the location of the currently electrified population. The estimated current electrification rate based on this method for South Sudan is around 11%. This electrification rate is higher than the rate reported by SE4ALL because of potential false positives like fires and gas flares. Therefore, to be conservative, the analysis uses the 2021 SE4ALL Global Tracking Framework as the baseline electrification rate, and the night-light images to identify the electrified settlements.

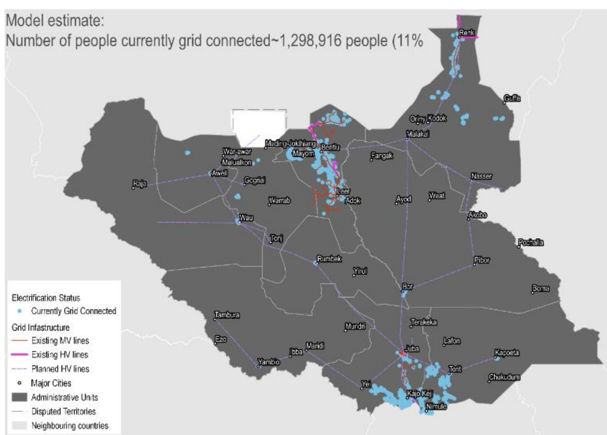
Figure 2: Night-light areas around settlement clusters



15. **To create the nightlight image shown above, a year's worth of night-time lights imagery based on monthly composites from 2018[8] is processed to create a single indicator of the likelihood of electrification (shown by the shaded green squares), with a resolution of around 500 meters**. The images are further filtered to find points significantly brighter than their surroundings, producing regions of access (black outlines). By overlaying this with population data (red pixels), it is possible to create disaggregated estimates of access. It is also possible to go further, using additional data to quantify not only access but also the percentage of connections within each area. Satellite imagery can therefore complement the end-user data available from household surveys such as the Multi-Tier Framework.

16. **The approach has several limitations, such as coarse resolution and large regional differences, which should be addressed in a more detailed electrification planning exercise for South Sudan.** In the methodology used in this high-level study, the granularity is limited by the amount of light that can be picked up from space. Industrial complexes and streetlights are bright, whereas satellite sensors may not be able to pick up light emitted from houses or offices. Off-grid sources may be particularly hard to capture because of the dimmer light they produce. This method also assumes all households in areas with visible light output are electrified which may not always be the case.

Figure 3: People with existing grid connections based on nightlights data



2.3 Methodology to Create Population "clusters"

17. In order to run the GEP model, existing population datasets were processed (and HRSL raster data in particular) to create population "clusters". A cluster is a bundle of pixelated areas in close proximity to each other that merge and create a vector polygon. Clusters – in contrast to gridded population – have various geometries and sizes and therefore better reflect the geography and behavior of human settlements.

2.4 Adding Attributes to Population Settlement Clusters

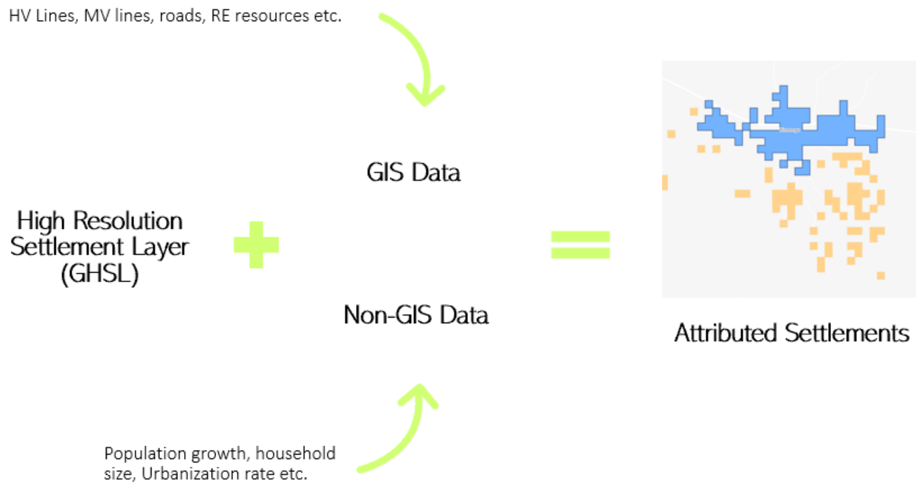
18. Regardless of the source's format, the population layer is eventually converted into a point layer, which means each point representing the center of the area it covers. In order to prepare the primary

[8] This is the most update nightlight satellite data for South Sudan.

input file to GEP model the values of the fundamental GIS datasets (see previous section) need to be extracted and attributed to each settlement (or point) respectively.

19. The extraction process is done in GIS environment using a plugin. This, however, involves various commands depending on the type of attribute to be extracted (e.g., zonal statistics, raster value to points, nearest neighbor etc.).

Figure 4: Methodology to determine population settlement clusters



2.5 Methodology to Estimate the Energy Demand of Health Facilities

20. **Classification of health facilities**: The classification process presented below is based on the idea that health facilities are grouped into four main generic categories[9]:

- **Type 4:** District/Referral Hospital (> 145 beds)
- **Type 3:** Rural Hospital (~55 beds)
- **Type 2:** Small Inpatient Clinic (~14 beds)
- **Type 1:** Rural Dispensary - No Inpatient (~4 emergency beds)

21. This categorization is consistent with the literature (see for example Franco et al.). It has also been adopted and used in the HOMER Powering Health Tool. In this example, we use three values to classify the health facilities accordingly. These include:

1. **"urban_mean"**: This is the average urban status {urban:1 or rural:0} for all clusters connected with each health facility. A value >0.5 indicates that a health facility serves a more urban settlement and thus is more likely to be of higher type.
2. **"pop_sum"**: This is the sum of the population in all clusters connected with each health facility (or else a theoretical "outpatient capacity" for each health facility). Higher potentially served population is likely to indicate higher type.

[9] The data is from WB Health GP, 2021

3. **"elecpop_sum"**: This is the sum of electrified population in all clusters connected with each health facility. This indicates - to some extent - the electrification status in the vicinity and thus can potentially be connected with the type of health facility.

22. **Assigning electricity requirements based on facility type:** Estimating electricity requirement per health facility is not an easy task considering the lack of quantitative data. In this example, we use the HOMER Powering Health Tool[10] interface to quantify potential electricity requirement (kWh/year) per type of health facility.

23. The estimated demand for each type of facility in kWh based on the 4 categories above is:

Type 1: Rural Dispensary = 5.7*365= 2081 kWh/year
Type 2: Small Inpatient Clinic = 13.9*365 =5074 kWh/year
Type 3: Rural Hospital= 37*365 = 13,505 kWh/year
Type 4: District/Referral Hospital=361.1*365 = 131,802 kWh/year

2.6 Limitations of GEP-OnSSET Model and Methodology

24. **The model takes existing generation and transmission infrastructure as static.** Though this approach is potentially more conservative, as it does not presuppose successful completion of large, complex infrastructure projects in a highly challenging environment, it also means that the model is unable to provide recommendations on transmission and generation infrastructure, even in the context of electrification.

25. **The modeling is based on residential and health facility demand only, and does not consider demand from commercial industrial, agricultural, or non-health public consumers.** This is due to data limitation as the model requires explicitly geo-referenced spatial data to incorporate these additional demand sources in the analysis, which is not available for most consumer categories. Hence a more rigorous demand assessment and load forecasting would be needed in future detailed studies.

26. **Demand and demand growth is for households and health clinics is based on assumptions and extrapolations.** Ground-level demand and consumption data based on surveys or utility records were not available for this study.

27. **The model does not allow for hybrid generation options.** This limits the different technologies that can be considered for a least-cost analysis. The model also does not provide any detailed outputs on design criteria like sizing and network design for mini-grids or standalone solutions.

28. **What the model assumes to be the existing "grid", is in reality a series of small, isolated urban island grids that closely resemble what would be normally thought of as a "mini-grid".** As a result, the distinction and cost comparison between grid and mini-grid is somewhat artificial and could lead to misleading results. For instance, in high-density areas near the existing grid (i.e. island grids in cities), the model compares the generation cost of those grids to the hypothetical cost of a mini-grid and then determines which technology is cheapest. Under this approach, in a scenario in which grid generation

[10] The HOMER Powering Health Tool is a free online model to create initial designs of electric power systems for health care facilities that can be accessed via https://poweringhealth.homerenergy.com/

costs remain high, even households near the grid would be best served by a new mini-grid. Taken to its logical conclusion, this would effectively mean building parallel mini-grids next to or over existing isolated grids. In reality, a true least-cost approach might entail simply replacing the expensive existing grid generation source with a cheaper mini-grid-style generation source (e.g. PV + battery), and then extending that existing grid to connect new households. This would essentially be a combination of "mini-grid" on the generation side but "grid" on the electrification side under the terminology of the model and would likely lead to cheaper overall outcomes.

3 GEP Model Results for South Sudan

29. **The GEP model was used to assess four scenarios for South Sudan, reflecting different assumptions about household demand and the cost of grid electricity supply.** The four scenarios are summarized below. The different levels of household demand in the four scenarios are based on the Multi-Tier Framework (MTF)[11]. The low-demand scenario assumes demand to be 219 kWh and 803 kWh per year per households for rural and urban settlements respectively. The high-demand scenario assumes rural and urban settlements demand to be 1,365 kWh and 3,599 kWh per household, respectively (accounting also for non-household demand from health facilities denoted by a '+' in the table below).The high cost of grid electricity supply is considered to be representative of current situation in South Sudan and a lower cost of grid electricity supply (US$0.10/kWh) is taken to represent a more optimistic potential future with greater diversity in generation sources and transmission lines to transport their energy.

Table 2: Multi-Tier Framework Demand Tiers

Tier 1 = 38.7 kWh/household/year+
Tier 2 = 219 kWh/household/year+
Tier 3 = 803 kWh/household/year+
Tier 4 = 2117 kWh/household/year+
Tier 5 = 2993 kWh/household/year+

Table 3: Summary of Specifications of Four Electrification Scenarios

Scenario	Multi-Tier Framework Demand Tiers		Estimated cost of grid generation in 2030 (US$/kWh)
	Urban	Rural	
E1	'Low' demand scenario (Tier 4)	'Low' demand scenario (Tier 2)	'Low' cost scenario (US$ 0.10 per kWh)[12]

[11] The Multi-Tier Framework (https://www.worldbank.org/en/topic/energy/publication/energy-access-redefined) looks at the multiple dimensions of access to capture information about the quantity and quality of services. It also captures the multiple modes of delivering energy access from grid to off-grid and the range of cooking methods and fuels people use.

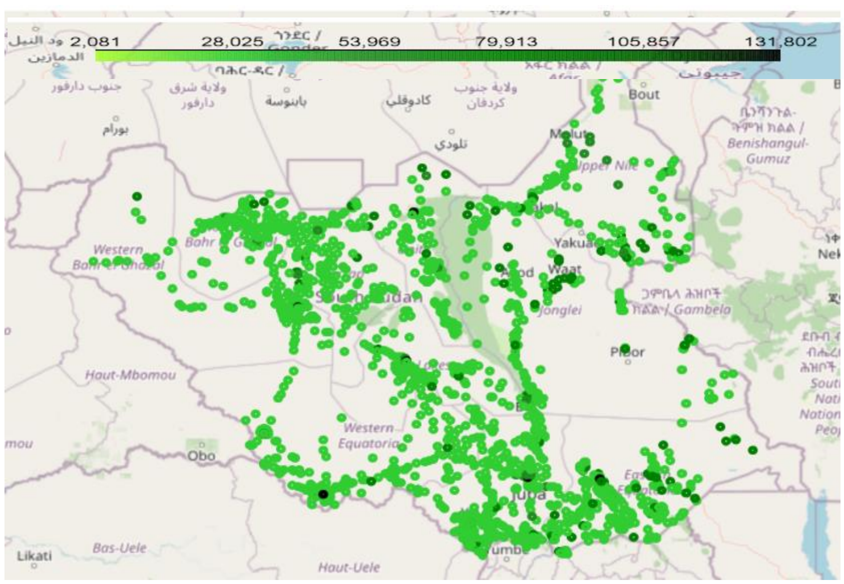
[12] C. Taliotis et al., "An indicative analysis of investment opportunities in the African electricity supply sector - Using TEMBA (The Electricity Model Base for Africa)," Energy Sustain. Dev., vol. 31, pp. 50–66, 2016

E2	'Low'	'Low'	'High' cost scenario (US$ 0.37 per kWh)
E3	'High' demand scenario (Tier 5)	'High' demand scenario (Tier 3)	'Low'
E4	'High'	'High'	'High'

30. **The 'High' and 'Low' demand scenarios presented above were also run with the consideration of planned HV lines in the Least-Cost Electricity Supply Expansion model**. The results for these scenarios were however near identical to the scenarios described above and so the inclusion of planned HV had no impact in the overall model results. Please see the annex for detailed results under additional sensitivity analyses.

31. **Demand for health facilities located all around the country was estimated by using a set of generic assumptions due to the lack of geo-referenced demand data.** The aggregated demand (in kWh/year) from health facilities were assigned to the nearest settlement cluster. Additionally, the analysis does not incorporate demand from other sources like social infrastructure, commercial and industrial facilities. Instead, model scenarios with high residential demand (described above) were run to assess the potential impact of demand from non-residential consumers.

Figure 5: Yearly estimated demand (in kWh) for health facilities in South Sudan



Source:[*https://datapane.com/u/shaky/reports/hf-elec-demand-southsudan*](https://datapane.com/u/shaky/reports/hf-elec-demand-southsudan)

3.1 Summary of Model Results

Figure 6: Target Electrification rate by technology type, 2025 and 2030

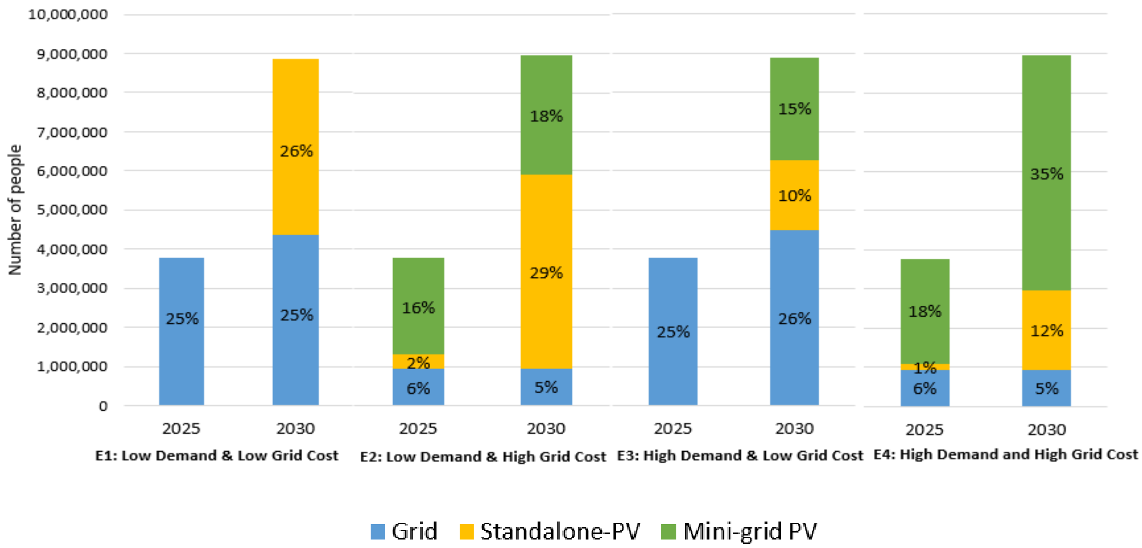
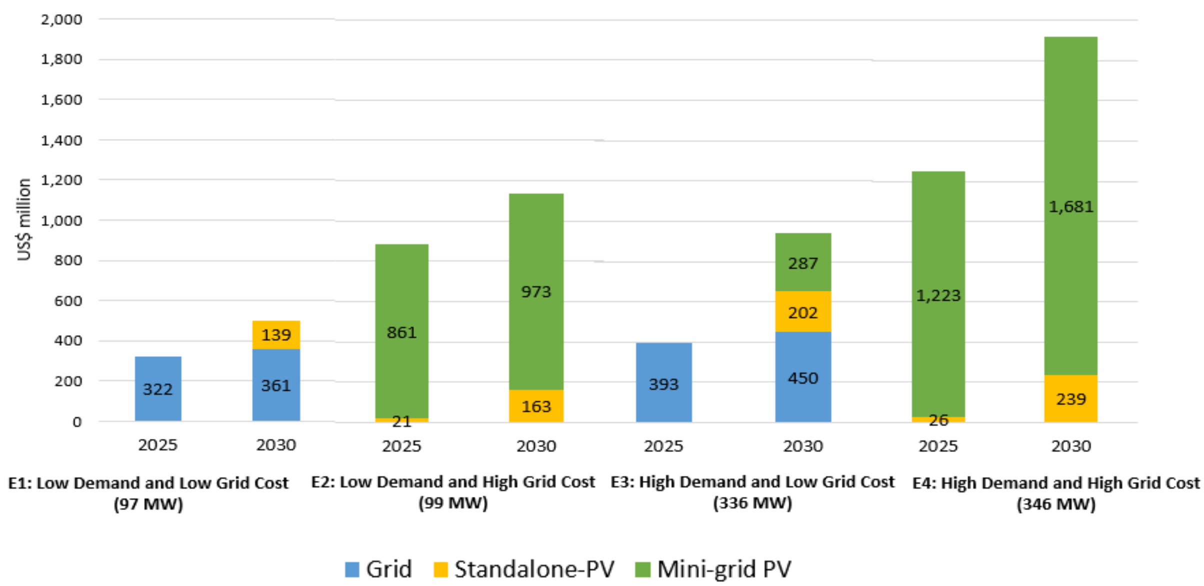


Figure 7: Estimated cumulative investment costs, 2025 and 2030



3.2 Geographic Representation of Model Results

Figure 8: E1 - Low Demand and Low Grid Cost

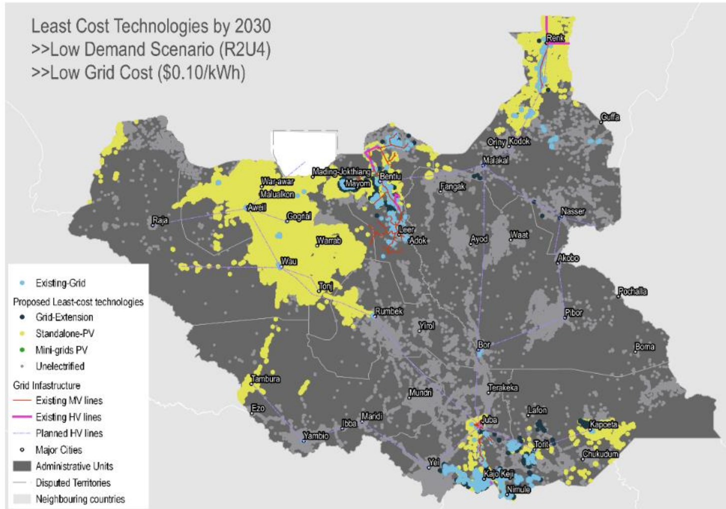


Figure 9: E2- Low Demand and High Grid Cost

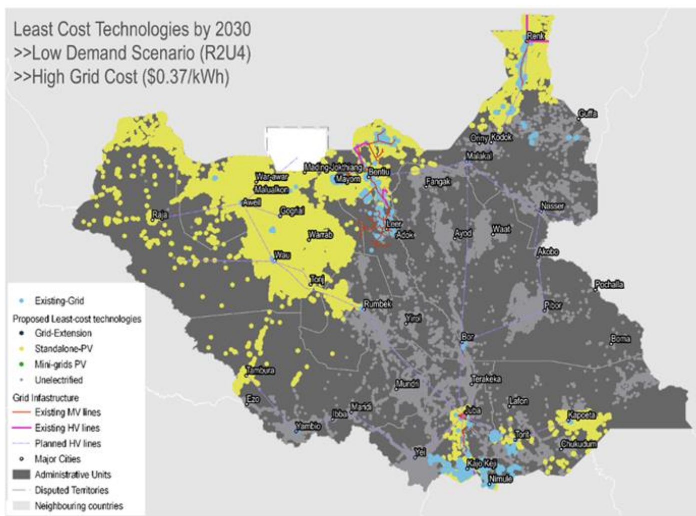


Figure 10: E3- High Demand and Low Grid Cost

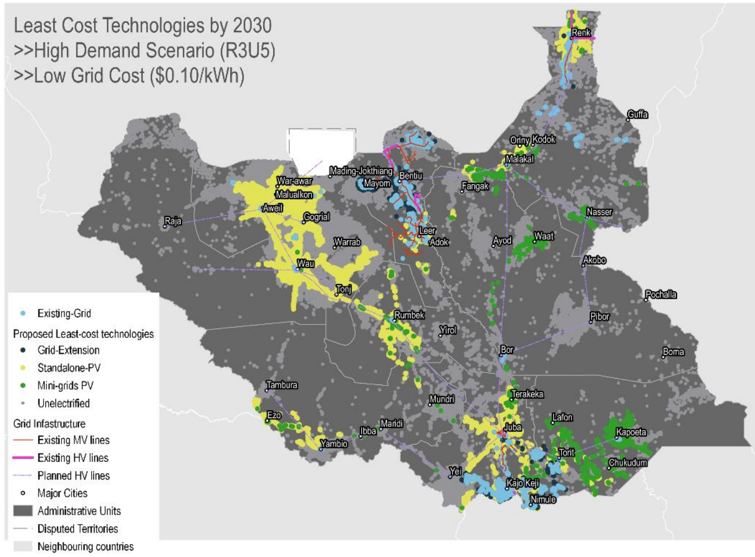
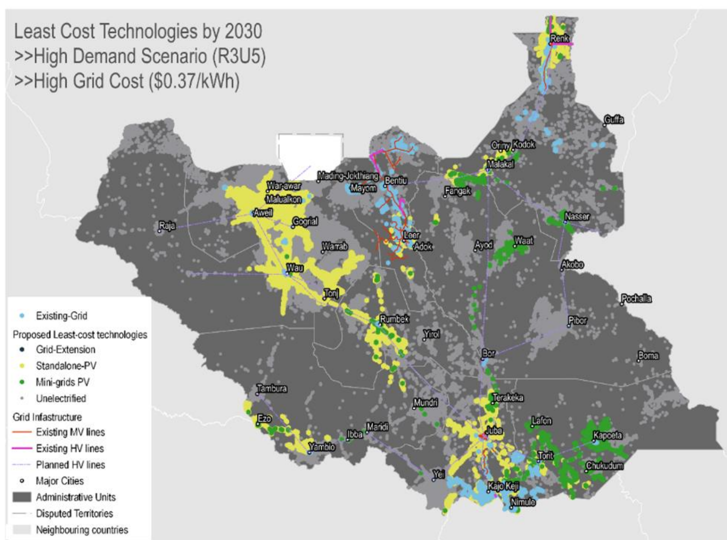


Figure 11: E4- High Demand and High Grid Cost



3.3 Key Takeaways from Model Results

32. The main takeaways from the results are as follows:

a) **Achieving the targets of 25 percent electricity access by 2025 and 50 percent by 2030 requires a dramatic increase in the pace of electrification.** Achieving 25 percent by 2025 will require connecting 600,000 people *per year,* accounting for population growth. Moving from there to 50 percent access by 2030 would require a further acceleration to around 1 million people per year gaining access between 2026 and 2030.

b) **The least-cost solutions recommended under both high- and low-demand scenarios include a significant scale-up of off-grid solutions.** These include stand-alone solar home systems and solar PV mini-grids, based on renewable energy sources whose supply costs are decreasing. Even in the scenarios with the highest levels of new access coming from the grid, around 25% of households will need to be connected by mini-grids or standalone systems by 2030.

c) **If the cost of grid generation does not significantly decrease, grid electrification will not be a viable least-cost solution even in areas that already have some grid infrastructure already exists.** This is mainly due to the current high cost of South Sudan's thermal-dominated generation mix, which, despite the country's oil wealth, is one of the most expensive in the region at USc 0.37/kWh. If South Sudan's existing grid infrastructure is to be part of future electrification, a shift to a lower-cost generation mix will be required.

d) **The assumed level of demand also has a significant impact on the least-cost electrification path.** Higher demand growth will shift the least-cost option for more isolated communities from standalone solar systems to mini-grids, significantly raising investment costs. The sensitivity to demand underscores the need for high-quality demand assessments to feed into future electrification planning exercises, especially for larger, non-household users such as industrial, commercial, agricultural, or mining users.

e) **The model results show that it is least-cost to expand the grid in areas nearby the existing grid infrastructure when grid generation cost is low and demand is high.** However, when the grid generation cost is too high, most of the settlement clusters are connected by either standalone solar PV systems (when demand is low) or mini-grids (when demand is high). The mini-grid settlements are not too far from the grid, suggesting that mini-grids can be considered an interim solution for these settlements. In some cases, existing grid infrastructure may also be subsumed into a new mini-grid (or vice-versa), which may reduce investments costs somewhat compared to the values presented here. Where mini-grids are selected as either interim solutions before grid arrival or are merged with existing grid infrastructure, grid-compatibility and potential system upgrade costs will need to be taken into account**.**

   To achieve 50% total electrification by 2030, South Sudan will require US$500 million to US$1,920 million in investment, depending on household energy demand and the cost trajectory of grid-connected generation.

4 Additional Sensitivity Analysis Scenarios

4.1 Sensitivity Analysis 1: Lower Grid Cost with Planned HV lines

33. The analysis above shows that the least-cost electrification technology is, unsurprisingly, sensitive to grid cost. When grid cost is high, households living in higher-density areas will be connected most cheaply through mini-grids. Though grid costs might not reach the USc 10 levels used in two of the previous scenarios, it seems reasonable to assume some improvement in costs as development partners reengage in South Sudan's electricity sector and support generation diversification. Therefore, this sensitivity analysis shows how decreasing grid cost would impact the results. The tables below show the technology solution mix when the grid cost is at USc 15, USc 25, and USc 30 with low demand scenario (Urban Tier 4 and Rural Tier 2).

Low demand scenario at 15 USc of grid cost, including planned HV:

	PopConnected 2020	NewPopConnected2025	PopConnected 2025	NewPopConnected2030	PopConnected 2030
Grid	931,000	1,106,485	1,702,462	206,303	1,505,210
Standalone-PV				4,495,157	4,495,157
Mini-grid PV		1,729,402	2,064,425	391,985	2,859,966
Total	931,000	2,835,887	3,766,887	5,093,445	8,860,333

Low demand scenario at a 25 USc of grid cost, including planned HV:

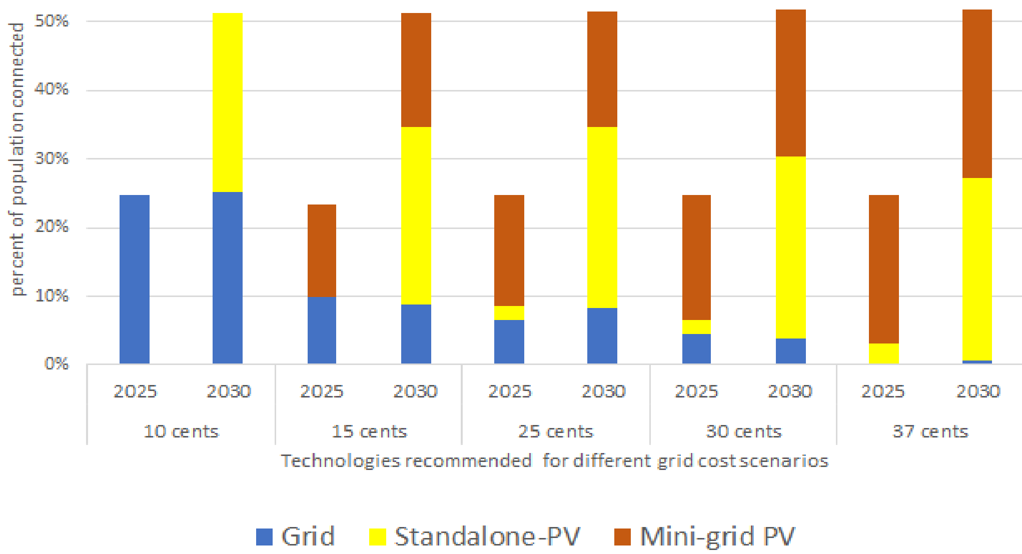
	PopConnected 2020	NewPopConnected2025	PopConnected 2025	NewPopConnected2030	PopConnected 2030
Grid	931,000	428,795	1,001,469	194,881	1,421,872
Standalone-PV		289,618	289,968	4,541,255	4,541,255
Mini-grid PV		2,117,474	2,475,450	403,262	2,942,242
Total	931,000	2,835,887	3,766,887	5,139,398	8,905,369

Low demand scenario at a 30 USc of grid cost, including planned HV:

	PopConnected 2020	NewPopConnected2025	PopConnected 2025	NewPopConnected2030	PopConnected 2030
Grid	931,000	287,867	672,325	91,987	671,150
Standalone-PV		306,351	329,048	4,589,585	4,589,585
Mini-grid PV		2,241,669	2,765,513	505,913	3,691,195
Total	931,000	2,835,887	3,766,887	5,187,874	8,954,762

34. The results shows that the grid and mini-grid are targeting similar consumers. When the grid cost is lower, more people will be connected via grid and fewer people will be connected via mini-grid. The electrification share of off-grid systems is largely unaffected, as the population density and income profiles of these households are well-suited to neither grid nor mini-grids.

Figure 12: %pop connected by different technologies under different grid cost assumptions



4.2 Sensitivity Analysis 2: Higher Current Rate of Electrification (11% based on model estimates) and Planned HV Lines Included in the Model

35. Assuming a higher rate of current electrification does not result in significant changes in terms of the proposed least-cost solutions. The difference was mainly in the number of new connections required to reach the target rate for both 2025 and 2030 and their related costs.

High demand scenario with current electrification rate of 11% including planned HV

	PopConnected 2020	NewPopConnected2025	PopConnected 2025	NewPopConnected2030	PopConnected 2030
Grid	1,161,020	-	-	-	-
SA_PV		787,989	818,047	2,934,657	2,934,657
MG_PV		1,941,325	3,072,288	2,761,119	5,804,340
Total	1,161,020	2,729,315	3,890,335	5,695,777	8,738,998

4.3 Sensitivity Analysis 3: ambitious access target – 50% Electrification by 2025 and Universal Access by 2030

Low demand scenario and High Grid Cost

	PopConnected 2020	NewPopConnected2025	PopConnected 2025	NewPopConnected2030	PopConnected 2030
Grid	931,000	-		-	
SA_PV		4,780,936	4,780,936 (31%)	9,081,517	12,844,137 (72%)
MG_PV		2,840,720	2,840,720 (18%)	1,157,174	5,016,212 (28%)

Total	931,000	6,956,657	7,621,657	10,238,692	17,860,350

Low demand scenario and Low Grid Cost

	PopConnected 2020	NewPopConnected2025	PopConnected 2025	NewPopConnected2030	PopConnected 2030
Grid	931,000	3,216,190	3881190 (25%)	616,443	4497634 (25%)
SA_PV		3,979,090	3979090 (26%)	8,839,375	12818466 (75%)
MG_PV					
Total	931,000	7,195,280	7,860,280	10,000,069	17,860,350

High demand scenario with High Grid Cost

	PopConnected 2020	NewPopConnected2025	PopConnected 2025	NewPopConnected2030	PopConnected 2030
Grid	931,000(7%)				
SA_PV		1,945,399	1,945,399 (13%)	3,981,006	5,684,939 (32%)
MG_PV		5,162,694	5,162,694(33%)	6,106,249	12,175,410 (68%)
Total	931,000	7,108,094	7,773,094	10,087,255	17,860,350

High demand scenario with Low Grid Cost

	PopConnected 2020	NewPopConnected2025	PopConnected 2025	NewPopConnected2030	PopConnected 2030
Grid	931,000	3,216,190	3881190 (25%)	616,443	4497634 (25%)
SA_PV		1,514,377	1514377 (10%)	4,145,900	5660277 (32%)
MG_PV		2,162,167	2162167 (14%)	5,540,270	7702438 (43%)
Total	931,000	6,892,735	7,557,735	10,302,614	17,860,350

Annex

Number of people connected for the four major scenarios

E1: Low Demand and Low Grid Cost	Pop Connected 2020	New Pop Connected 2021-2025	Pop Connected 2025	New Pop Connected 2026-2030	Pop Connected 2030
-	931,000	2,835,887	3,766,887 (25%)	598,289	4,365,176 (25%)
Standalone-PV		-	-	4,495,157	4,495,157 (26%)
Mini-grid PV		-	-	-	-
Total	931,000	2,835,887	3,766,887	5,093,446	8,860,334
E2: Low Demand and High Grid Cost	**Pop Connected 2020**	**New Pop Connected 2021-2025**	**Pop Connected 2025**	**New Pop Connected 2026-2030**	**Pop Connected 2030**
Grid	931,000	2,567	939,063 (7%)	14804	953,867 (6%)
Standalone-PV		369,982	369,982 (2%)	4,589,585	4,959,567 (29%)
Mini-grid PV		2,463,337	2,463,337 (16%)	583,484	3,046,821 (18%)
Total	931,000	2,835,887	3,766,886	5,187,874	8,960,255
E3: High Demand and Low Grid Cost	**Pop Connected 2020**	**New Pop Connected 2021-2025**	**Pop Connected 2025**	**New Pop Connected 2026-2030**	**Pop Connected 2030**
Grid	931,000	2,835,887	3766887 (25%)	724,070	4,490,958 (26%)
Standalone-PV		-	-	1773042	1,773,042 (10%)
Mini-grid PV		-	-	2,633,870	2,633,870 (15%)
Total	931,000	2,835,887	3,766,887	5,130,982	8,897,870
E4: High Demand and High Grid Cost	**Pop Connected 2020**	**New Pop Connected 2021-2025**	**Pop Connected 2025**	**New Pop Connected 2026-2030**	**Pop Connected 2030**
Grid	931,000	-	-	-	-
Standalone-PV		154,615	243,824 (2%)	1,871,103	1,871,103 (11%)
Mini-grid PV		2,681,272	3,523,062 (23%)	3,306,075	7,072,963 (41%)
Total	931,000	2,835,887	3,766,887	5,177,179	8,944,067

Investment requirement for each technology

E1: Low Demand and Low Grid Cost	Pop Connected 2025	Capacity 2025 (MW)	Investment 2025 (mil.USD)	Pop Connected 2030	Capacity 2030 (MW)	Investment 2030 (mil.USD)	Cumulative investments by 2030 (mil. USD)
Grid	25%	114	322	25%	21	39	361
Standalone-PV	-	-	-	26%	76	139	139
Mini-grid PV	-	-	-	-	-	-	-
Total	25%	117	322	51%	97	178	500
E2: Low Demand and High Grid Cost	Pop Connected 2025	Capacity 2025 (MW)	Investment 2025 (mil.USD)	Pop Connected 2030	Capacity 2030 (MW)	Investment 2030 (mil.USD)	Cumulative investments by 2030 (mil. USD)
Grid	-	-	-	-	-	1	1
Standalone-PV	3%	2	21	27%	77	142	163
Mini-grid PV	22%	112	861	26%	21	112	973
Total	25%	114	882	52%	99	255	1,137
E3: High Demand and Low Grid Cost	Pop Connected 2025	Capacity 2025 (MW)	Investment 2025 (mil.USD)	Pop Connected 2030	Capacity 2030 (MW)	Investment 2030 (mil.USD)	Cumulative investments by 2030 (mil. USD)
Grid	25%	169	393	26%	35	57	450
Standalone-PV	-	-	-	10%	110	202	202
Mini-grid PV	-	-	-	15%	190	287	287
Total	25%	169	393	51%	336	546	939
E4: High Demand and High Grid Cost	Pop Connected 2025	Capacity 2025 (MW)	Investment 2025 (mil.USD)	Pop Connected 2030	Capacity 2030 (MW)	Investment 2030 (mil.USD)	Cumulative investments by 2030 (mil. USD)
Grid	-	-	-	-	-	-	-
Standalone-PV	2%	3	26	11%	116	213	239
Mini-grid PV	23%	166	1,223	41%	228	458	1,681
Total	25%	169	1,249	53%	345	672	1,921

List of attributes that are extracted from the GIS data based on above method

Column	Unit	Description
Country	name	Name of the country in focus (e.g. Malawi)
NightLights	nW cm^−2 sr^−1	Average yearly value of stable night lights luminosity. Value is used (together with other parameters) to identify current electrification status of the settlement.
Pop	people	Number of people living in the settlement, as retrieved from the GIS data source (without calibration)
id	number	Unique identifier of each settlement
GridCellArea	sq.km	Area of the settlement; retrieved from population cluster development and processing
ElecPop	people	Number of people with access to electricity in the base year; Value is retrieved from the cluster development process
WindVel	m/s	Yearly average wind speed in the area of the settlement
GHI	kWh/m^2/year	Yearly average Global Horizontal Irradiation in the area of the settlement
TravelHours	hours	Travel time to nearest town of 50k people; in the case of (polygon) clusters this value represents the minimum distance at any direction
Elevation	m	Above sea level; in the case of cluster this value reflects the average elevation in the area of the settlement
Slope	deg	A product of DEM indicating terrain slope; in the case of cluster this value reflects the average slope in the area of the settlement
ResidentialDemandTIerCustom	kWh/capita/year	Electricity demand target based on a custom-based, bottom up approach (if available)
LandCover	1 to 15	Type of land cover as defined by the source data; refer to documentation
SubstationDist	km	Distance to nearest sub-station; based on best available GIS data sources in the base year; in the case of (polygon) clusters this value represents the minimum distance at any direction

Column	Unit	Description
CurrentHVLineDist	km	Distance to nearest HV line; based on best available GIS data sources in the base year; in the case of (polygon) clusters this value represents the minimum distance at any direction
CurrentMVLineDist	km	Distance to nearest MV line; based on best available GIS data sources in the base year; in the case of (polygon) clusters this value represents the minimum distance at any direction
RoadDist	km	Distance to nearest (primary/secondary) road; based on best available GIS data in source in the base year; in the case of (polygon) clusters this value represents the minimum distance at any direction
X_deg	Deg	Longitude
Y_deg	deg	Latitude
Transformer Dist	km	Distance to nearest service transformer; based on best available GIS data sources in the base year; in the case of (polygon) clusters this value represents the minimum distance at any direction
PlannedMVLineDist	km	Distance to nearest planned MV line; based on best available GIS data; in the case of (polygon) clusters this value represents the minimum distance at any direction
PlannedHVLineDist	km	Distance to nearest planned HV line; based on best available GIS data; in the case of (polygon) clusters this value represents the minimum distance at any direction
Hydropower Dist	km	Distance to nearest site with identified small scale hydropower potential
Hydropower	kW	Technical potential of the nearest small scale hydropower site
HydropowerFID	number	Unique identified of the nearest small scale hydropower site
IsUrban	0,1,2	Indicates Urban/Rural status of the settlement; 2: urban, 1 and 0: rural; 0 refers to small rural settlements while 1 in larger rural settlements or peri-urban areas, but the model does not differentiate

Column	Unit	Description
PerCapitaDemand	kWh/capita/year	Electricity demand target based on urban/rural status and targets set for each type of settlement
HealthDemand	kWh/year	Electricity demand target to support health related activities in the settlement
EducationDemand	kWh/year	Electricity demand target to support education related activities in the settlement
AgriDemand	kWh/year	Electricity demand target to support agriculture related activities in the settlement
ElectrificationOrder	number	Indicates the loop in which the settlement gets electrified; serves only developer purposes
Conflict	0-4	Indicates conflict level, which in turn affects costing of electrification; 0: no conflict 4: total unrest; parameter is not used in the GEP
CommercialDemand	kWh/capita/year	Electricity demand target to support commercial activities in the settlement
ResidentialDemandTier1	kWh/capita/year	Electricity demand target for Tier 1
ResidentialDemandTier2	kWh/capita/year	Electricity demand target for Tier 2
ResidentialDemandTier3	kWh/capita/year	Electricity demand target for Tier 3
ResidentialDemandTier4	kWh/capita/year	Electricity demand target for Tier 4
ResidentialDemandTier5	kWh/capita/year	Electricity demand target for Tier 5

List of all non-GIS input parameters used in the model

Variable	Value	Description
Start_year	2020	
End_year	2030	
End year electrification rate target	0.5	
Intermediate target year	2025	
Intermediate electrification rate target	0.25	
PV cost adjustment factor	0.6	
Urban target tier	5 or 4	
Rural target tier	3 or 2	
Prioritization	5	5 = least cost, 4 = forced grid within buffer only, 6 = forced grid within buffer & least cost out of the buffer zone
Auto intensification distance	2	Buffer distance (km) for automatic intensification if choosing prioritization 1
discount_rate	0.08	
pop_threshold	0	
pop_start_year	13300000	the population in the base year (e.g. 2018)
pop_end_year	17254370	the projected population in the end year (e.g. 2030)
urban_ratio_start_year	0.17	the urban population ratio in the base year (e.g. 2018)
urban_ratio_end_year	0.241	the urban population ratio in the end year (e.g. 2030)
num_people_per_hh_urban	7.1	the number of people per household expected in the end year (e.g. 2030)
num_people_per_hh_rural	6.4	the number of people per household expected in the end year (e.g. 2030)
elec_ratio_start_year	0.07	the electrification rate in the base year (e.g. 2018)
urban_elec_ratio	0.13	urban electrification rate in the base year (e.g. 2018)

rural_elec_ratio	0.05	rural electrification rate in the base year (e.g. 2018)
grid_generation_cost	0.10 or 0.37	This is the grid cost electricity USD/kWh as expected in the end year of the analysis
grid_power_plants_capital_cost	1183	The cost in USD/kW to for capacity upgrades of the grid-connected power plants
grid_losses	0.14	The fraction of electricity lost in transmission and distribution (percentage)
base_to_peak	0.8	The ratio of base grid demand to peak demand (percentage)
existing_grid_cost_ratio	0.1	The additional cost per round of electrification (percentage)
diesel_price	0.5	This is the diesel price in USD/liter as expected in the end year of the analysis
sa_diesel_capital_cost	770	Stand-alone Diesel capital cost (USD/kW) as expected in the years of the analysis
mg_diesel_capital_cost	650	Mini-grid Diesel capital cost (USD/kW) as expected in the years of the analysis
mg_pv_capital_cost	2950	Mini-grid PV capital cost (USD/kW) as expected in the years of the analysis
mg_wind_capital_cost	3850	Mini-grid Wind capital cost (USD/kW) as expected in the years of the analysis
mg_hydro_capital_cost	3500	Mini-grid Hydro capital cost (USD/kW) as expected in the years of the analysis
sa_pv_capital_cost_1	9620	Stand-alone PV capital cost (USD/kW) for household systems under 20 W
sa_pv_capital_cost_2	8780	Stand-alone PV capital cost (USD/kW) for household systems between 21-50 W
sa_pv_capital_cost_3	6380	Stand-alone PV capital cost (USD/kW) for household systems between 51-100 W
sa_pv_capital_cost_4	4470	Stand-alone PV capital cost (USD/kW) for household systems between 101-200 W
sa_pv_capital_cost_5	6950	Stand-alone PV capital cost (USD/kW) for household systems over 200 W
mv_line_cost	7500	Cost of MV lines in USD/km

lv_line_cost	4450	Cost of LV lines in USD/km
mv_line_capacity	33	Capacity of MV lines in kW/line
lv_line_capacity	0.24	Capacity of LV lines in kW/line
lv_line_max_length	0.5	Maximum length of LV lines (km)
hv_line_cost	58000	Cost of HV lines in USD/km
mv_line_max_length	50	Maximum length of MV lines (km)
hv_lv_transformer_cost	25000	Cost of HV/MV transformer (USD/unit)
mv_increase_rate	0.1	percentage
max_grid_extension_dist	50	Maximum distance that the grid may be extended by means of MV lines
annual_new_grid_connections_limit_intermediate	99999999	This is the maximum amount of new households that can be connected to the grid in one year (thousands)
annual_new_grid_connections_limit_end	999999999	This is the maximum amount of new households that can be connected to the grid in one year (thousands)
grid_capacity_limit_end	999999999	This is the maximum generation capacity that can be added to the grid in one year (MW)
grid_capacity_limit_intermediate	491	This is the maximum generation capacity that can be added to the grid in one year (MW)
GIS data: Administrative boundaries		Delineates the boundaries of the analysis.
GIS data: DEM		Filled DEM (elevation) maps are use in a number of processes in the analysis (Energy potentials, restriction zones, grid extension suitability map etc.).
GIS data: Hydropower		Points showing potential mini/small hydropower potential. Provides power availability in each identified point.
GIS data: Land Cover		Land cover maps are use in a number of processes in the analysis (Energy potentials, restriction zones, grid extension suitability map etc.).
GIS data: Night-time Lights		Dataset used to,identify and spatially calibrate the currently electrified/non-electrified population.

GIS data: Population		Spatial identification and quantification of the current (base year) population. This dataset sets the basis of the ONSSET analysis as it is directly connected with the electricity demand and the assignment of energy access goals
GIS data: Roads		Current road infrastructure is used in order to specify grid extension suitability.
GIS data: Solar GHI		Provide information about the Global Horizontal Irradiation (kWh/m2/year) over an area. This is later used to identify the availability/suitability of Photovoltaic systems.
GIS data: Substations		Current Substation infrastructure is used in order to specify grid extension suitability.
GIS data: Existing grid		Current grid network
GIS data: Planned grid		Planned/committed grid network extensions
GIS data: Travel-time		Visualizes spatially the travel time required to reach from any individual cell to the closest town with population more than 50,000 people.
GIS data: Wind velocity		Provide information about the wind velocity (m/sec) over an area. This is later used to identify the availability/suitability of wind power (using Capacity factors).