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Optimizing Spatial Input Data for Techno-Economic Modeling of Least-Cost Electrification Pathways in Zambia

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ABSTRACT

Zambia's current population is approximately 19.4 million, growing at an annual rate of about 2.9%. Only 40% of Zambia's population has access to electricity, leaving roughly 11.7 million people without modern energy services. Since 2008, the Rural Electrification Authority of Zambia embarked on an ambitious program to increase the rural electrification rate from 11% to about 51% by 2030. However, this goal may not be realized at the current electrification rate. This article presents an analysis of techno-economic electrification pathways for Zambia using the Open-Source Spatial Electrification Toolkit. While the Rural Electrification Authority of Zambia aims to increase electrification from 11% to 51%, this research targets achieving 100% access to electricity by 2030 to meet the United Nations Sustainable Development Goal 7.1. The study involves national-scale modeling of lowest-cost technology options for 750,000 distinct population settlement clusters, based on the least cost of electricity to supply electricity to settlements using a range of technologies while benchmarking the study with the Global Electrification Platform. In this study, data for Zambia was improved and validated by enhancing the accuracy of population clusters and the electricity grid network. This was achieved by combining several new datasets from gridfinder.org, Geo-Referenced Infrastructure, and Demographic Data for Development - three, WorldPop, the United States Agency for International Development Demographic and Health Surveys and engaging with the national Zambian Electricity Supply Company. The results are benchmarked against the latest publicly available scenarios in the Global Electrification Platform using the same version of the Open-Source Spatial Electrification code, thus only testing the effects of the population and grid datasets on the results. Remarkably great similarity of about 99.95% of the total investment cost requirement between the standalone solar system and the grid extension was realized by 2030 but with a 10% decrease in investments in grid extension. Standalone solar systems have seen a corresponding rise, primarily because the gridfinder.org dataset identified numerous false positive grids which refer to instances where a dataset incorrectly identifies areas as having existing electrical grid infrastructure when, in reality, they do not. Standalone solar systems are found to be less costly than grid extensions by a factor of 10, saving almost US$33 million.

KEYWORDS

"Electrification, Pathways, Population, OnSSET, Modeling, Technologies, Investment"

INTRODUCTION

Zambia is hydropower dependant and often faced with electricity shortages that spur from drought while solar energy remains unexplored. To avoid over-dependence on the grid, there is a need to find cost-effective solutions to achieve universal electricity access by 2030, leveraging solar and other energy resources. Zambia has an installed power capacity of about 2800 MW, of which 85% is hydropower-based [1], while solar power accounts for 1% and backup diesel power accounts for 1%. The remaining 15% is supplied by non-renewable fuels/fossil fuels [2]. The Zambia Electricity Supply Company manages these limited (ZESCO), which is also the sole electricity supply company and controls the independent power producers (IPPs) [3].

With an average Global Horizontal Irradiance (GHI) of 2045 kWh/m^2 [4] and an average wind speed of 6.42m/s [5] and water resources of 105 billion m^3/year [6], Zambia has a huge potential to exploit solar, wind, and hydropower. Although the current installed hydropower capacity is about 2,800 (MW), the existing hydropower potential exceeds 6,000 MW [7]. The planned capacity is set to be realized by 2030, but this is highly dependent on how well the electrification plans that have been put in place are implemented by the Rural Electrification Authority (REA).

Due to the changing climate, which causes droughts and floods throughout the country [8], Zambia's dependency on hydropower may soon be challenged hence the need for least-cost electricity options.

. Characteristics of climate change like drought can lead to unreliable electricity supply, electricity shortages, and even load-shedding or power blackouts [9]. But the potential for solar, coupled with the continued price reduction of solar products, and easy access to green financing globally [10], [11] offers opportunities to include variable renewable energy (VRE) in the future generation mix, as well as solar home systems.

The last population census in Zambia was conducted in 2010, and the population was estimated to be about 13.6 million people [12]. Based on a population growth rate of 2.9%, the population is estimated to be about 19.47 million [13], [14]. Zambia has an average national electricity access rate of only about 40%, with 77% of the population in urban areas having access to electricity, and as little as 11% in rural areas [13]. This shows that most of the Zambian people, especially those in rural areas, remain without electricity and therefore points to the need to model electrification solutions that would help improve the electrification access rate in rural areas.

Previous studies on electrification programs in Zambia, by the Japan International Cooperation Agency (JICA), USAID - Southern Africa Energy Program (SAEP) cited the existence of the Rural Electrification Master Plan (REMP) for rural electrification in Zambia up to the year 2030 [1], [15], [16]. Further, these studies provided a qualitative analysis of the least cost electrification options required for Zambia to achieve universal access by 2030 but showed that there is a need to conduct more detailed studies as the scenarios developed had some limitations. Although these studies gave a trend analysis that could assist with better decision-making, these can be improved by using reliable models based on assumptions of costs of technologies, new transmission, distribution infrastructure, etc.

The Rural Electrification Authority of Zambia (REA) is a Zambian statutory body created under the Act of Parliament No. 20 of 2003 whose mandate is to provide electricity infrastructure in rural areas with suitable resources and technologies to increase electricity access, productivity, and general quality of life. REA's goal is to increase the electrification rate from 11% to 51% by 2030 [17] through several support programs and initiatives. In 2008, Zambia embarked on an electrification program through REA at an estimated cost of US$ US$ 1,103 million over a period, from 2008 to 2030. On average, about US$ 50 million was needed annually until 2030. The source of the funding was mainly international financial institutions, governments, government agencies, and donors. To kick start the Rural Electrification Master Plan (REMP), JICA funded Zambia with an initial US$50 million in 2008 [15]. The aim of the Rural Electrification Master Plan (REMP) is to combat poverty in rural areas through electrification to supply electricity to about 1,217 rural growth centers identified throughout Zambia. Further, the REMP also aims at developing twenty-nine (29) mini hydropower sites in the Northern, Luapula and North-Western provinces of Zambia [18]. The electrification program in Zambia has undoubtedly yielded positive results but, can be improved if the electrification or investment plans are supported by improved spatial electrification pathways using least-cost options. Zambia is still far away from achieving the targets set out in 2008 by the REA through the REMP, hence the need to come up with more reliable information and tools to allow policymakers in the Government and the private sector to make informed decisions [19].

Previous studies that show the versatility and applicability of the Open-Source Spatial Electrification Toolkit (OnSSET) tool in various African contexts, helping to plan and optimize electrification efforts include Malawi, where electrification pathways were modeled to achieve SDG 7 and highlighting the role of open access data in geospatial electrification planning [20]. In Tanzania, the tool was used to conduct research by incorporating high-resolution demand and techno-economic optimization evaluated solar micro-grids to incorporate justice in electricity pricing [21]. In Nigeria, a geographical information system-based approach for electrification planning was applied, with a focus on the least-cost technology options for improving access to electricity services [22]. In Kenya, OnSSET was used to model the least-cost technology options for electrification pathways to address medium- and long-term energy planning problems in Kenya [23].This study addressed some of the electrification challenges and shortfalls identified in JICA [15] and USAID [1] providing opportunities to inform national policy and electricity access using the Open-Source Spatial Electrification Toolkit (OnSSET) tool. OnSSET is a bottom-up, optimization, energy systems modeling framework that uses Geospatial Information Systems (GIS) to propose an electrification pathway that meets an anticipated level of electricity demand in 2030 [24]. OnSSET thus provides a spatial analysis of alternative electrification pathways that consider population distribution, population density, current grid network, technology potential, and investment cost, solar, battery, diesel, hydro, and/or wind) energy resources, technology costs, etc. [24].

The analysis includes a new bottom-up WorldPop population distribution [25] and a comparison of electrification solutions between OnSSET using Geo-referenced Infrastructure and Demographic Data for Development (GRID3) population clusters [26]. The grid dataset was enhanced by combining OpenStreetMap data and gridfinder.org to eliminate the grid lines that do not exist. Our OnSSET results are compared to the high-demand global electrification platform - GEP scenario, which uses Multi-Tier Framework data from the World Bank (categorized as Urban Tier 5 and Rural Tier 3). These tiers are selected for residential demand only. Parameters, such as solar, hydro, diesel costs, and connection costs, remained unchanged [27]. All parameters, like diesel costs, solar costs, hydro costs, and connection costs, remained unchanged.

This study aims to develop an improved model, and analysis of electrification pathways, with updated population and grid network location, and to show the extent to which population assumptions and grid assumptions influence the optimal technology choice. The objectives that help address the study are:

1. **Achieve Universal Electrification**: To model and propose pathways for achieving 100% electrification in Zambia by 2030, aligning with Sustainable Development Goal 7 (SDG7).
2. **Techno-Economic Analysis**: To conduct a comprehensive techno-economic analysis using the Open-Source Spatial Electrification Toolkit (OnSSET) to identify the most cost-effective electrification technologies and strategies.

3. **Improve Data Accuracy**: To enhance the accuracy of population clusters and grid network data by integrating multiple new datasets, thereby improving the reliability of the electrification models.
4. **Benchmarking**: To benchmark the study's results against the Global Electrification Platform (GEP) scenarios, ensuring the findings are robust and comparable with global standards.
5. **Policy Support**: To provide valuable insights and tools for policymakers and planners in Zambia, aiding in the formulation of effective electrification policies and investment decisions.
6. **Open Data and Replicability**: To ensure transparency and replicability by making all input datasets and the code used in the study openly available for other researchers and stakeholders.

These objectives aim to address the significant challenge of energy poverty in Zambia by providing a detailed and actionable roadmap for achieving universal access to electricity.

The significance of this study is that:

1. **Addressing Energy Poverty**: With only 40% of Zambia's population having access to electricity, this study targets a critical issue of energy poverty, aiming to provide modern energy services to the remaining 60%, which is essential for improving quality of life and economic development.
2. **Alignment with SDG7**: The study's goal of achieving 100% electrification by 2030 aligns with Sustainable Development Goal 7 (SDG7), which aims to ensure access to affordable, reliable, sustainable, and modern energy for all.
3. **Techno-Economic Analysis**: By using the Open-Source Spatial Electrification Toolkit (OnSSET), the study provides a comprehensive techno-economic analysis, offering valuable insights into the most cost-effective electrification pathways for Zambia.
4. **Policy and Planning Tool**: The findings can serve as a crucial tool for policymakers and planners in Zambia, helping them to make informed decisions about investments in electrification projects.

Besides the significance of this work and its contribution to the field of rural electrification, the study addresses a critical issue, aligning with global goals, and employing innovative methods of rural electrification. Some key innovative approaches used include**;**

1. **Use of Advanced Modeling Tools**: The study employs the OnSSET toolkit, which allows for detailed national-scale modeling of electrification options, considering various technologies and their costs.
2. **Improved Data Accuracy**: By integrating new datasets from sources like gridfinder.org, GRID3, WorldPop, and USAID Demographic and Health Surveys, the study enhances the accuracy of population clusters and grid networks, leading to more reliable results.
3. **Benchmarking with GEP**: The study benchmarks its results against the Global Electrification Platform (GEP), ensuring that the findings are robust and comparable with global standards.
4. **Open Data and Replicability**: All input datasets and the code used in the study are openly available, promoting transparency and allowing other researchers to replicate and build upon the work.
5. **Cost Optimization**: The study identifies a 10% decrease in investments needed for grid extension by correcting false positive grids, highlighting the potential for significant cost savings and more efficient allocation of resources.

MATERIALS AND METHODS

OnSSET is an energy modeling tool that optimizes electrification pathways in a spatially explicit manner. By considering datasets related to population distribution, renewable energy resources (solar, wind, and small hydropower), population cluster distance to existing grid networks, land cover, and technology costs, OnSSET estimates and visualizes cost-effective solutions. Table 1 shows the significance of these different datasets in OnSSET analysis.

Table 1. Significance of datasets in OnSSET analysis

Dataset	Significance of OnSSET Analysis
Population density & distribution	This dataset provides the spacial identity and quantity of clusters that need electrification (current year) according to the required electrification level and assigned energy consumption in OnSSET.
Administrative boundaries	This provides the name of the area that is being targeted for modeling and indicates the exact position of the boundary of the analysis.
Existing grid network	Specifies the position of the grid network and is used to calculate the distance between the grid and electrified/unelectrified clusters. The distance and cost of electricity from the grid is used to estimate the cost of supplying electricity to households via grid extension compared to other technologies
Substations	The substation infrastructure data is used to identify and calibrate the population and extend the grid to clusters that are not electrified. It also helps establish grid extension suitability.
Roads	The road infrastructure data is used to calibrate the current electrified population and helps indicate the suitability of the grid extension.
Planned grid network	This gives an outlook of future plans for grid extension, which includes substations, power plants, or other major infrastructure and developments in the area, such as mines and quarries
Nighttime lights	This gives an indicator of areas that are electrified and used to calibrate datasets
GHI	Global Horizontal Irradiation (GHI), measured in kWh/m2/year, over an area gives solar availability and helps establish the suitability of deploying Solar Photovoltaic systems.
Wind speed	The wind velocity, usually measured in meters per second (m/sec) over an area, helps to firstly establish the availability of wind resource and second, the suitability of deploying wind energy using the capacity factor.
Hydro power potential	This gives an indicator of power availability for deployment of mini/small hydropower. This includes environmental, social, and topological restrictions.
Travel time	This is the travel time required to reach from individual cells to a cluster of more than 50,000 people. This is usually visualized spatially.
Elevation Map	Filled Digital Elevation Model (DEM) maps play a crucial role in various analysis processes, including assessing energy potentials, identifying restriction zones, and creating grid extension suitability maps
Land Cover	Land cover maps are used to analyze the Energy potentials, and restriction zones and develop grid extension maps etc.

In this study, OnSSET is used to evaluate, based on the available database resources that are highlighted in Table 1, or other key technology determinant criteria like, the distance of that target cluster from the grid and selecting the appropriate technology with the least cost. The model's least-cost solution evaluates the expenses associated with the supply of power to settlements. This comparison includes central grid connections, stand-alone solar PV systems for individual homes, and electrification of communities using hybrid mini-grid systems (combining solar, battery, diesel, hydropower, and/or wind). Both this study and GEPv2 [28] have maintained the OnSSET default values of the costs associated with the different energy technologies available for OnSSET to select from. The updated version of the GEP, known as GEPv2, features improved data accuracy, enhanced algorithms, a user-friendly interface, and high scalability to handle larger datasets with seamless integration [29].

The economic viability of each technology option is dependent on the electricity demand, the distance from the grid, and the population density of the unelectrified communities[*]. To define a demand threshold for each household in the unelectrified community, this study adopted the Multi-Tier Framework (MTF) developed by the Energy Sector Management Assistance Program (ESMAP), a global knowledge and technical assistance program administered by the World Bank [30]. The MTF proposes levels of energy access (kWh/household/year) needed to achieve certain levels of energy services, these levels are presented as tiers in the MTF. In this study, to benchmark against the GEPv2 High-demand option scenario; the Urban-T5 Rural-T3 is adopted [13]. A top-down demand target, with relatively high electricity access of Tier 5 for urban areas and Tier 3 for rural areas to each household was applied. The unelectrified clusters are targeted to reach one Tier higher than the current average consumption level of electrified households, and rural settlements, assigned to ensure that the entire population is supplied with electricity. OnSSET then calculates the electricity needs of each cluster according to the number of households in the cluster and whether it is considered urban or rural, according to the selected scenario, and in this case, MTF is Urban-T5 or Rural-T3 was selected.

Table 2 shows the power demands, the minimum power capacity, and the level of services that can be provided at each tier per household [24], [30].

Table 2. Electricity access tiers of the multi-tier framework.

Tier	Demand kWh/household/year	Minimum Power Capacity (Watts)	Service level
1	38.7	3	Basic phone charging and lighting
2	219	50	lighting, phone charging, television, and fan
3	803	200	Tier 2 and any medium-power appliances
4	2117	800	All Tier 3 service and some high-power appliances
5	2,993	2,000	All Tier 4 and very high-power appliances

In this study and the GEPv2 models, Tier 5 is used to depict the expected average annual household electricity consumption of urban households, and Tier 3 is used to depict the expected average annual household electricity use of rural households. The demand in each cluster is calculated by OnSSET then calculates the electricity needs of each cluster according to the number of households in the cluster according to the selected scenario option, either Urban-T5 or Rural-T3.

The main objective of this study is to present an improved model, and therefore analysis of electrification pathways, with updated population and grid network location, and to show the extent to which population assumptions and grid assumptions influence the optimal technology choice. To do this a two-way data improvement was implemented, focusing on (i) a review of the population clusters and (ii) a validation of the grid connections in Zambia. Figure 1 gives an overview of the methodology adopted in this study. The study focused on improving the population clusters and the grid-connection network. Figure 1 shows the population cluster and grid improvement approach for reliable electrification pathways.

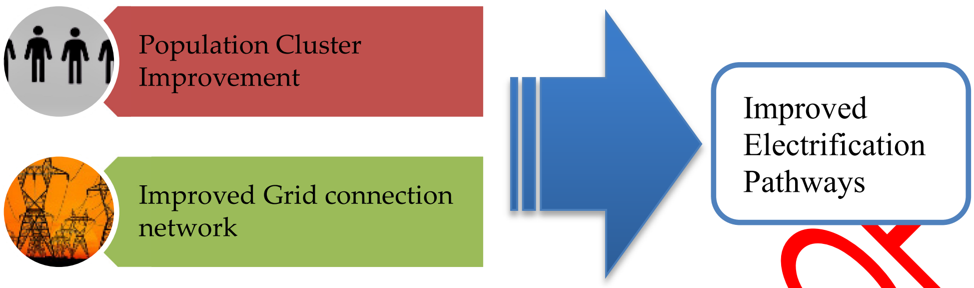

Figure 1. Electrification pathway improvement approach

Some key innovative approaches used include the use of the advanced modeling Tool, OnSSET toolkit, improved data accuracy, benchmarking with the Global Electrification Platform (GEP), the use of open access data, and cost optimization. The following sections highlight how the population and grid were improved.

Population Cluster Improvement

Accurate population data is essential for OnSSET, as it directly impacts electricity demand in any scenario or model. Factors such as population size, location, density, local resources, and electrification status of households significantly influence the outcomes of electrification analyses.

In this study, the population datasets were enhanced by combining various sources and approaches. Specifically, population clusters from the recently released GRID3 [26] were utilized to detect buildings and shapes of settlements. Notably, this dataset has improved the accuracy and comprehensiveness of data for settlement detection in Africa. The boundaries of the GRID3 settlements are characterized by naturally rounded shapes. To populate these settlement clusters, the new bottom-up WorldPop population distributions were employed [25]. Furthermore, electrification rates, total population figures, and rural/urban ratios were calibrated with the methodologies and values employed in OnSSET and GEPv2. This calibration ensures comparability between the datasets.

This approach aimed to reduce false positives and negatives in the data. False positives occur when a cell in the dataset appears to be populated but is uninhabited. This can happen due to mistaking building structures for trees, shadows, rocks, water edges or indeed relocated temporary structures. This can make population settlements seem larger or indicate clusters where none exist. False negatives happen when existing settlements and populations are missing, usually due to image processing failures or outdated satellite imagery [31].

Figure 2 illustrates this with two examples. In Figure 2 a, many false positives are shown in Luangwa West National Park, like the blue GEP clusters are actually rocks or trees. In Figure (b), settlements outlined in orange are missing in the GEP data but are confirmed to have permanent structures via satellite imagery. The GRID3 clusters have a more natural shape compared to the GEP cluster's square shapes.

Figure 2 illustrates a comparison between GEP population clusters (using GRID3 settlement clusters and Facebook High-Resolution Settlement Layer (HRSL) data), combined with the bottom-up population counts from WorldPop. In Figure 2 a, numerous false positives within a national park, while Figure 2b highlights several false negatives where settlements remain undetected in the HRSL data. The image is developed using the 2022 version of Mapbox [32].

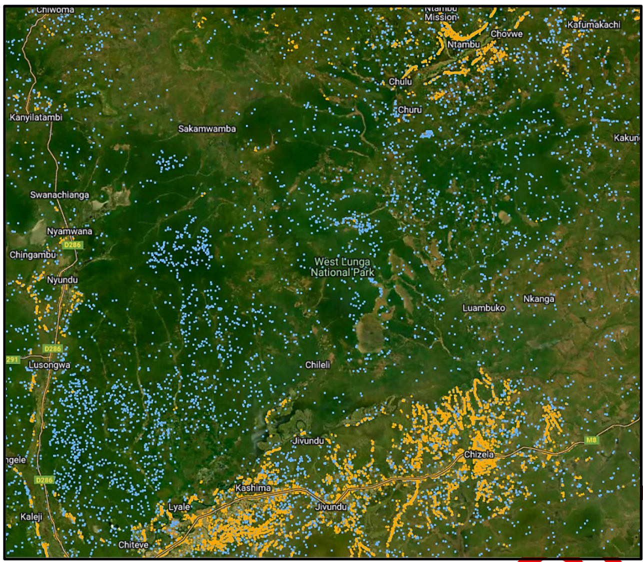

Figure 2 a

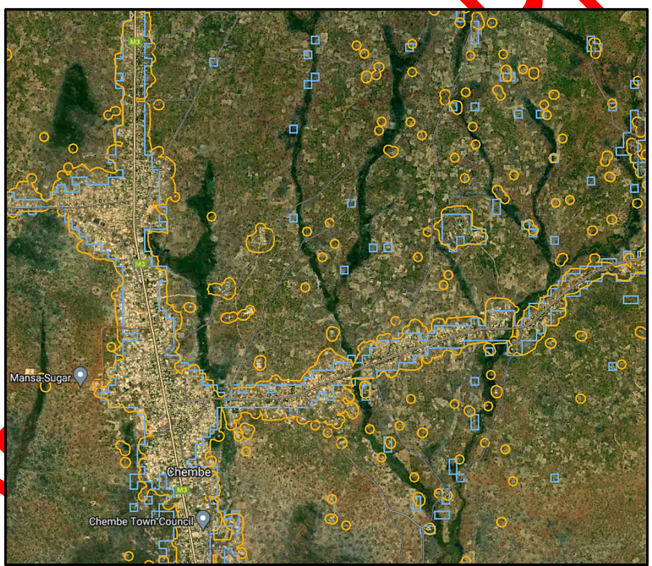

Figure 2 b

GEP Clusters with Facebook HRSL GRID3 Clusters + WorldPop *(This study)*

Figure 2. Comparison of GEP population clusters (GRID3 settlement clusters and Facebook HRSL data), combined with WorldPop

Grid Network Improvement

The population cluster way of validating the grid network aims to reduce false positives (detecting non-existent grid networks) and false negatives (which do not include the existing grid network) in the OnSSET representation. This GEPv2 grid dataset was validated using primary data from the Zambia Energy Regulation Board. Additionally, the GEPv2 dataset is enhanced by integrating Nightlight data and OpenStreetMap data from the Visible Infrared Imaging Radiometer Suite (VIIRS) satellite, which helps eliminate many incorrect lines from gridfinder.org through manual inspection with multiple overlaid data layers. The improvements in the population cluster and datasets of the grid network as illustrated in Figure 3. In Figure 3 a, the existing GEP clusters (represented by blue lines) superimpose onto the enhanced GRID3 clusters. The orange areas highlight clusters that were not captured by the GEP dataset and its underlying Facebook High-Resolution Settlement Layer (HRSL) population rasters. Figure 3 b, illustrates the OpenStreetMap (OSM) High Voltage (HV) lines (blue), which both models utilize, alongside the updated grid data (shown in green) used in this study. In contrast, the gridfinder.org (2020) data (red lines) reveals false positive grid lines that, upon inspection, do not actually exist [28].

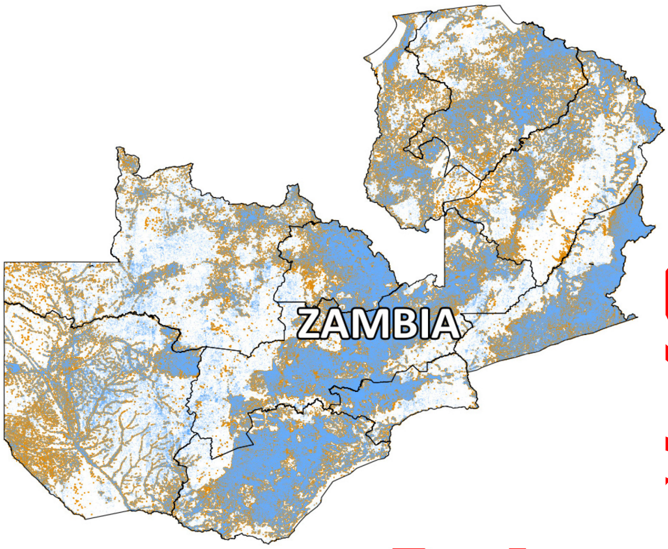

Figure 3 a

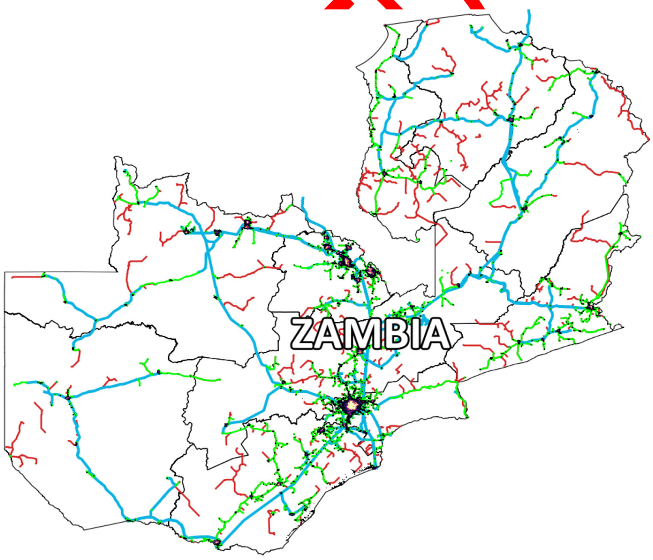

Figure 3 b

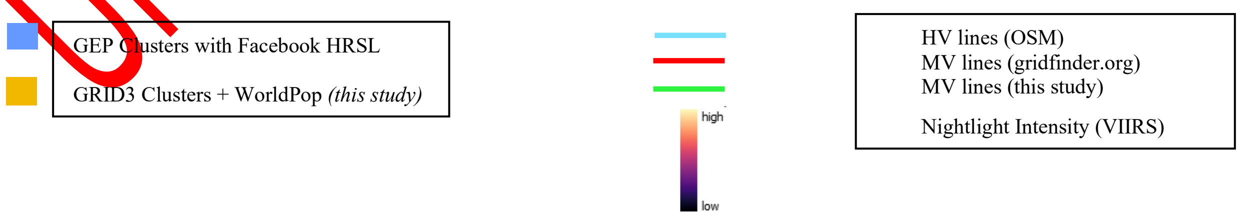

Figure 3. Improved GEP clusters and updated grid

RESULTS AND DISCUSSION

Running the OnSSET model with updated grid and population data, aiming to achieve 100% universal access by 2030. It focused on meeting Tier 5 demand in urban areas and Tier 3 demand in rural regions, aligning with the MTF developed by ESMAP. OnSSET model determined the least-cost technology options for 2030, as illustrated in Figure 4. The results indicate extensive use of stand-alone PV, solar PV hybrid mini-grids, and grid extensions across Zambia. A minimal number of mini hydro grids hydro were also identified as optimal but were excluded from the map and charts for simplicity, as they serve fewer than 1,000 people.

The total investment costs are remarkably similar between the GEPv2 and this study, with only a 0.047% difference, as shown in Figure 5. Despite a 10.0% decrease in grid investments, standalone solar systems have seen an 8.7% increase and solar mini-grid investments have risen by 9.3%. Additionally, the total population per technology shows a 10.0% reduction in grid investments, a 7.4% increase in stand-alone solar PV systems, and a 9.9% increase in solar mini-grid investments. With OnSSET calculations set to achieve a 100% electrification rate by 2030, the system calibrates, based on the least cost to add as many solar systems and solar mini-grids as possible. However, leveraging on the cost of solar systems in comparison to grid extension systems, solar home systems are quicker, to install and more reliable than hydropower and easier to finance because of their low investment cost. Further, solar systems are more viable to supply the rural areas because of the prevailing low energy demand in the rural areas.

These discrepancies are due to the gridfinder.org dataset identifying numerous false-positive grids (shown as red lines in Figure 4), which incorrectly suggests that grid extension to population clusters is feasible over shorter distances. Figure 5 presents optimized technology choices for 750,000 settlement clusters. Blue portions indicate areas where grid extension is the most cost-effective, orange represents regions where standalone solar systems are the areas of the cheapest, and green shows where solar hybrid mini grids are the most economical [32].

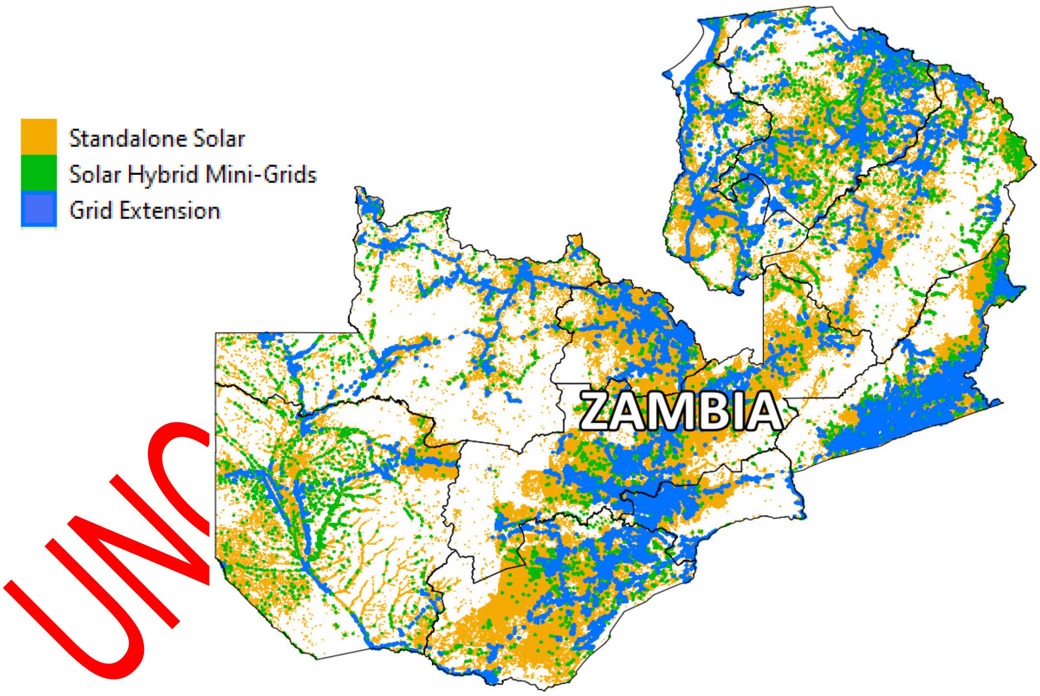

Figure 4. Optimal Electricity Access Technology in 2030

In Figure 6, the total number of people with access to grid electricity is 650,357 (4%) less than this study, the Solar Hybrid mini-grids and shows remarkably close results with this study having electrified about 10,5853 people (9.9%) more than the GEPv2 using Solar Hybrid Mini-grids. However, this study utilized more stand-alone solar to provide electricity to 544,209 people (7.4%) more than those supplied by Stand Alone Solar in the GEPv2 model.

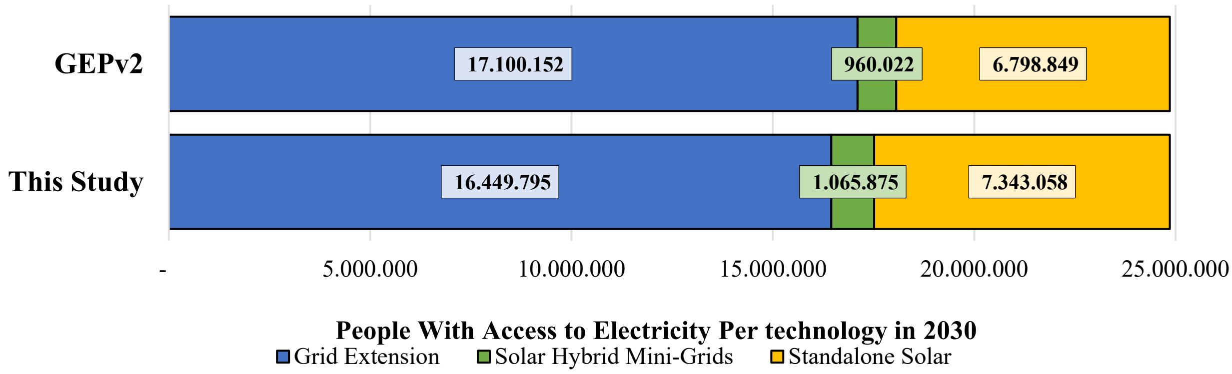

Figure 5. Total Electrified Population per Technology in 2030 (universal access) [32]

Figure 7 shows that this study allocates about 297 million (9.1%) grid extensions, less than the GEPv2. On the Solar Hybrid Mini-Grids, this study has allocated about 33 million (9.1%) more than the GEPv2. Finally, this study has increased the investment in Standalone Solar systems by about 261 million (8.7%) compared to the GEPv2 model.

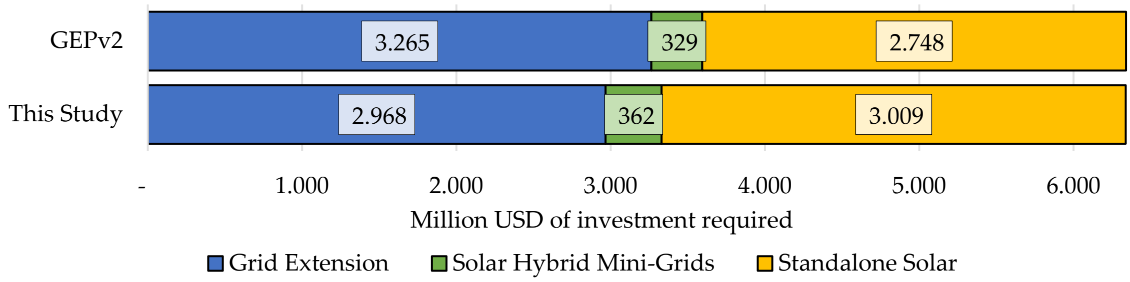

Figure 6. Breakdown of total investment costs and population per technology between this study and the GEP (please note that charts are not 100% stacked) [32].

CONCLUSION(S)

Zambia's marginal electricity supply to only 40% of its population constrains economic growth because more than 11.7 million people remain without access to modern energy services. Apart from economic benefits, people's health is also compromised because of using unclean cooking and lighting methods. This study improves the spatial input data accuracy for techno-economic modeling of least-cost electrification pathways in Zambia using ONSSET and found that, when benchmarked against the GEP model, and with similar total investment cost requirement by 2030, but with a 10.0 % decrease in investments in grid extension and a proportionate increase in investments in standalone solar systems, a 100% electrification rate is still achieved by 2030.

A few areas that require focus are firstly, reducing Zambia's dependency on grid electricity, because hydropower project turnaround time is over several years while standalone PV systems that can be implemented quickly are still unexplored. Secondly, the monopoly enjoyed by the state electricity generation firm, Zambia Electricity Supply Company (ZESCO) inhibits the growth of the SMEs and the Private Sector (Energy Developers). Thirdly, the inability of local financial institutions to finance the required investment by 2030 implies that total energy access by 2030 may depend on either external grants or external debt. Fourthly, in the specter of climate change and drought, and floods, hydropower is unreliable compared to solar investment. More investment in solar energy is encouraged.

This study addresses the critical issue of energy poverty in Zambia, where only 40% of the population has access to electricity. By targeting 100% electrification by 2030, it aligns with Sustainable Development Goal 7 (SDG7). Using the Open-Source Spatial Electrification Toolkit (OnSSET), the study provides a comprehensive techno-economic analysis to identify cost-effective electrification pathways. The findings serve as a valuable tool for policymakers and planners. Innovative approaches used include advanced modeling tools, improved data accuracy, benchmarking with the Global Electrification Platform (GEP), open data for transparency and replicability, and cost optimization by correcting false positive grids, leading to significant cost savings.

This study is limited to grid improvement and population cluster improvement only, but this can be extended to several other variables like costs, capacity factors, etc. Further, out of several tires, only Urban-T5 Rural-T3 is analyzed. This study can be extended to other ESMAPs Multi-Tier Framework (MTF) scenarios.

While previous studies show that the REA plans to upscale the grid network have a longer turnaround time against the agreed timelines, the researchers infer that this has led to low electrification rates. This study shows that even with a 10.0 % decrease in investment in grid extension, a proportionate increase in investment in standalone solar systems can still achieve 100% electrification faster than depending on hydropower projects, that also have high capital costs. This shows that Zambia needs to leverage the short turnaround time for solar installations to leapfrog their electrification rates to 100% by 2030. Further, even with a financial investment plan allocating about US$ 1,103 million (approximately US$50 million per year from 2008 to 2030) to finance 1,217 Rural Growth Centers - RGCs, the Rural Electrification Master Plan (REMP) has not been achieving its annual electrification targets because of financial dependency on grants from donors.

DECLARATION

Some of these results are submitted to the EU H2020-funded project LEAP-RE website [32].

ACKNOWLEDGMENT

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APPENDIX

Supplementary Materials for the supporting this work can be downloaded at: European Commission H2020 funded project LEAP-RE website LEAP-RE Research and Innovation Action (RIA) Joint EU-AU report on the platform testing and validation activity, at https://www.leap-re.eu/wp-content/uploads/2024/01/LEAP-RE_D12.5-Joint_EU_AU_report_on_the_platform_testing_and_validation_activity_V1.pdf