National University of Lesotho

GIS-Based Electrification Planning for Lesotho using OnSSET/GEP

Tšepo Letebele 201400411

A dissertation submitted in partial fulfillment
of the requirements for the degree of

Master of Science in Sustainable Energy

Offered by the

Energy Research Centre
Faculty of Science & Technology

June 2023

Abstract

Universal access to clean and affordable modern electricity is a social and economic development challenge for many countries, especially in Sub-Saharan Africa. This study carries out an in-depth analysis of GIS-based electrification planning for Lesotho using OnSSET/GEP from 2020 to 2030 to support SDG 7. The analysis looks at how an electrification rate of 47.3% by 2020 can be improved to 100% by 2030 in order to contribute to the development of a visual, interactive and effective electrification master plan as part of a wider national integrated resources planning. The study results based on the LCOE calculations indicate that optimum electrification for Lesotho can be achieved using a blended mix of grid and off-grid technologies. Grid technology has an LCOE of around 0.087 US$/kWh while of-grid technologies have an LCOE in the range between 0.229 and 0.8 US$/kWh. The electrification technology mix from this study consists of existing and extended grid networks covering the majority of the lowlands and towns in the urban areas, stand-alone solar photovoltaic (PV) systems covering the majority of rural settlements, wind power mini-grids and hydropower mini-grids covering dense rural settlements.

The total investment required for Lesotho to attain universal access to electricity by 2030 is estimated at $401.54 million to be used for infrastructure, household connections and the generation of additional new capacity. Electrification through grid connections requires 65.81% of the total investment with off-grid technologies taking up the remaining 34.19% of the investment. Results further illustrate that stand-alone solar PV systems are the least-cost technology for off-grid connections that require around 95% of the total investment towards off-grid electrification technologies. The sensitivity analysis indicates that higher electricity demand and increased population growth rate require more electrification investments and usage of the grid and mini-grid technologies while lower demand requires less investment together with the usage of stand-alone solar PV systems. Moreover, reduced solar PV technology costs encourage the usage of solar PV systems, both stand-alone and mini-grids with less investment costs.

Acknowledgments

I would like to pass my sincere thanks to my supervisor, Associate Professor Leboli Zak Thamae for his relentless effort in guiding, supporting, and encouraging me throughout the period of undertaking this research study. His knowledge, wisdom and kindness helped me a lot in being able to undertake this study and complete it. I also pass my sincere gratitude to the NUL Energy Research Centre staff for always sharing their wisdom with me whenever I asked for their guidance and input towards this study.

To my friends and colleagues, I thank you for all the support that you showed me and for always being there for each other as we carried out our research studies. To my family, thank you very much for everything you have done for me throughout my life, I am who I am because of you. Above all, I thank GOD, the almighty, for his guidance, protection, blessings and grace as well as for helping me throughout my academic journey, especially when I was carrying out this study.

Acronyms

BAU - Business as Usual

BoS - Bureau of Statistics

CSV - Comma Separated Values

DoE - Department of Energy

EDM - Electricidade de Mocambique

GEP - Global Electrification Platform

GIS - Geographic Information System

GHI - Global Horizontal Irradiance

GoL - Government of Lesotho

HV - High Voltage

IRP - Integrated Resource Plan LCOE

- Levelized Cost of Electricity

LEC - Lesotho Electricity Company

LEWA - Lesotho Electricity and Water Authority

LHDA - Lesotho Highlands Development Authority

LV - Low Voltage

MV - Medium Voltage

OnSSET - Open-Source Spatial Electrification tool

PV - Photovoltaic

REU - Rural Electrification Unit

SDG - Sustainable Development Goals

SHS - Solar Home System

SSA - Sub-Saharan Africa

UN - United Nations

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1. Introduction

1.1 Background

As of 2021, there were still about 768 million people without access to electricity globally, with 78% of them being from Sub-Saharan Africa (SSA), 17% being from developing Asia and the rest of the world making up the remaining 5% [1]. Figure 1 illustrates how the lack of access to electricity has changed for about 20 years starting from the year 2000 up to 2021. The most significant improvement is seen in developing Asia as its access to electricity improved by 90% in the same period [2]. SSA, on the other hand, has shown no improvement in increasing electricity access. Instead, more people continued to have no access to electricity over these 20 years; in 2000 there were around 500 million people without access to electricity compared to the 597 million people in 2021. The increased number of people with no access to electricity came as a result of the rapidly increasing population in SSA, compared to the electrification rate over this period [3].

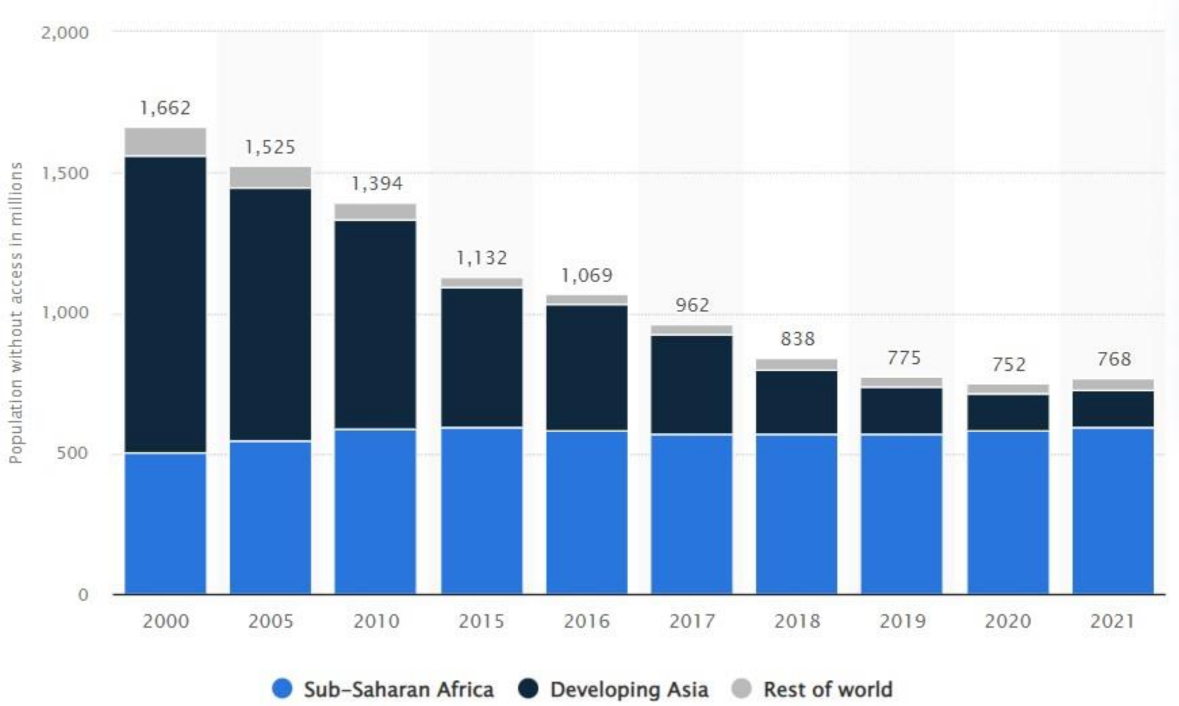


Figure 1: Trends in lack of access to electricity globally [1]

The majority of people without access to electricity in SSA are found in the rural areas which had around 25% electrification rate as of 2021 [4]. Generally, this low access to electricity in SSA inhibits both social and economic development within the region, as modern economic activities aligned with the current digital age cannot be adopted [5]. Furthermore, several constraints are imposed on people who lack access to electricity. Their quality of life cannot improve because they cannot adopt electricity-dependent technologies in some sectors such as education and agriculture among others [4, 6].

The global community has been trying to curb the problems associated with lack of access to electricity through the adoption of the United Nations (UN) sustainable development goals (SDGs) since their inception in 2015 [6, 7]. The target of SDG 7 is to ensure universal access to affordable, reliable, sustainable, and modern energy for all by 2030", with indicator 7.1.1 focusing on access to electricity [8]. This target shows the commitment of the global community in trying to achieve access to electricity by all by 2030 [9]. The annual access growth was faster in the last decade because of the development and implementation of electricity access infrastructure. However, the annual growth rate in access slowed from 0.8% to 0.5% within the same period due to the difficulties in reaching the un-served areas and the impact of COVID-19 [10]. These challenges as well as lack of planning, the difficulty in data acquisition and other challenges explain why there is still a very low electrification rate in SSA compared to the rest of the world [11].

The World Bank database on global access to electricity stipulates that the Lesotho electrification rate is at 47.3% as of 2020 [12]. Of the electrified portion, 87% is the urban while about 10% of the rural population has access to electricity; this leaves the country with a significant portion of the population without access to electricity, especially in the rural areas [8]. The electricity sector is primarily overseen by different stakeholders from the government and the regulator to the utilities in generation, transmission and distribution. The Government of Lesotho (GoL), through the Department of Energy (DoE) of the responsible Ministry, is tasked with being responsible for developing and implementing the policies associated with energy throughout the country [13]. This ministry also established the Rural Electrification Unit (REU) in 2004 in an attempt to improve electrification in the rural areas of Lesotho mainly through grid extension. However, recently REU is attempting to install off-grid systems such as mini-grids and Solar Home Systems (SHS) as alternatives for grid extension for the rural communities. The regulator, the Lesotho Electricity and Water Authority (LEWA), is responsible for regulating and facilitating the delivery of affordable and sustainable electricity in Lesotho.

The Lesotho Highlands Development Authority (LHDA) is by far the sole generator of electricity within the country through its ’Muela hydropower plant with a capacity of 72 MW. However, Lesotho imports more than 50% of its peak electricity demand from ESKOM in

South Africa and from Electricidade de Mocambique (EDM) in Mozambique. The currently proposed and ongoing projects attempt to increase the generation capacity. They include a 70 MW solar plant at Ha-Ramarothole [14], a 110 MW wind farm by Hirundo Energy [15] and a One-Power 20 MW solar plant in Mafeteng [16], among others. The Lesotho Electricity Company (LEC), on the other hand, is tasked with the transmission and distribution of electricity using the utility's grid network. It is also responsible for the entire transmission and distribution network infrastructure and the customer interface services.

To ensure a sustainable provision of access to electricity to the population in the rural areas of Lesotho, a systematic, proper and detailed planning is required to get an optimum or costeffective option in selecting suitable technologies that generate and provide electricity to the people [17]. Such planning should be practical and economically feasible and be part of an integrated resource plan (IRP) [18]. It should differ from traditional methods used in planning for rural electrification as they require large sets of data that are area or location-specific thus highly expensive and labor intensive to acquire [4,8]. To overcome the challenges related to data acquisition, a geographic information system (GIS) is applied and several models have been developed in recent years to carry out GIS-based rural electrification planning [4,9,10]. One GIS-based electrification tool called OpeN Source Spatial Electrification Tool (OnSSET) was recently used by Isihak [17] to examine the evolution and application of the tool in Kaduna state, Nigeria. Korkovelos [11] also used the OnSSET tool to examine the role of open-access data in geospatial electrification planning and the achievement of SDG 7 in Malawi.

1.2 Problem Statement

Lesotho, like most SSA countries, has an electrification rate of around 47.3% of the population as of 2020, with the least electrified population residing in the remote, highly rugged and mountainous rural areas [22]. This electrification rate is mainly due to the expenses involved in electrifying such areas (where the majority of the population resides) through extending the grid without considering the social and economic conditions of such areas. Currently, extending the grid to small and highly dispersed load centers with negligible electricity consumption is still not economically feasible given the economic status of Lesotho. Moreover, the utility experiences overwhelming financial losses due to the expensive operation and maintenance costs associated with serving remote communities with poor purchasing power.

To address the lack of optimal rural electrification problem and to identify the most costeffective means of electrifying the rural communities, taking into consideration both the geographical and socio-economic characteristics of such communities [23], an electrification planning study is necessary.

1.3 Objectives and Research Questions

This study aims to use one GIS-based electrification tool called OpeN Source Spatial Electrification Tool (OnSSET) for rural electrification planning and demonstrate and evaluate its application in Lesotho. The main objective of this study was to use GIS data in modelling the electrification plan for rural areas in Lesotho to find the least costly means of electrifying rural communities either through grid extension, mini-grids or stand-alone systems to support the achievement of SDG 7. The other objective is to contribute to the development of a visual, interactive, and effective rural electrification master plan as part of a wider national integrated resource planning.

The study will therefore address the following research question:

a) What electrification strategy can Lesotho employ in an attempt to achieve universal access to electricity for all by 2030 and beyond in the least costly and sustainable manner, considering both the geographic and socio-economic characteristics of rural communities?

b) How can the Lesotho power sector be able to provide universal electricity access by 2030 and beyond using grid-based power, mini-grid systems, and stand-alone systems?

1.4 Study Justification

GIS-based rural electrification planning is important in an attempt to fast-track the achievement of universal access to electricity in order to support SDG 7. It provides policymakers with the basic guidelines for the efficient electrification policy frameworks and effective planning that considers geographic and socio-economic attributes which are area-specific. It may also suggest the resources availability in such areas. The OnSSET/GEP software used in this study considers all these attributes together with the costs of electrification infrastructure as the input data and in turn, gives out the least costly solutions for electrifying the communities. Different stakeholders such as the policy-makers within the government, independent power producers, the regulator, the electricity utility and the rural electrification agency within the energy sector may greatly benefit from this study results which may help them to identify the most ideal technology (grid-extension, mini-grids or stand-alone systems) to use in electrifying the rural areas. This will be based on resource availability, investment costs and the tier level of such communities from the multi-tier framework of access to electricity, together with geographic and socioeconomic characteristics.

1.5 Report Structure

The study report is arranged in such a way that the next chapter reviews the literature on GISbased electrification planning, where the modelling tools such as Network Planner, SOLARIS, REM and OnSSET are evaluated. Chapter 3 presents the GIS data preparation for Lesotho and discusses the OnSSET/GEP methodology used to run and analyse the least-cost electrification strategy that Lesotho can explore to reach a 100% electrification rate by 2030. The next chapter focuses on the OnSSET/GEP simulation results from the reference scenario and other scenarios from the sensitivity analysis generated. It further discusses the results of the study and makes conclusions and recommendations, based on the outcomes of this study.

2. Literature Review

2.1. GIS-based Electrification Planning

Electrification planning is one way that can ensure access to electricity in a more sustainable manner. Therefore, it is crucial for any country as it contributes to its socio-economic development. To improve energy access within a region or a country, demographics, spatial orientation and economic status of such places need to be taken into consideration, thus the need arises to employ GIS-based electrification planning [9]. GIS is a combined set of both hardware and software tools built and integrated to capture, store, manage, manipulate, analyse and digitally present geographic data and the related attribute information [11]. It is also able to relate different sources through the utilization of index variables, space and time. This kind of electrification planning allows assessments that analyse sustainable energy-related geographic information while also facilitating remote sensing to derive the availability of resources and energy generation potentials that would otherwise not be available publicly [17]. Furthermore, GIS provides clear illustrations of the results, using interactive maps, and accommodates the filling of data gaps, thus providing an understanding of an effective sciencepolicy interface.

Considering the context of this study, several similar studies focus on energy planning and resource assessment for the rural areas at regional and global levels. However, they do not specifically focus on rural electrification in Lesotho. At the regional level, Szabo et al. [10] assessed different energy solutions for off-grid rural areas of Africa, using a spatial model to look for the least costly electrifying option between diesel generators, solar PV systems and grid extension. The study sets boundaries within reasonable constraints, based on cost-optimal options for grid extension. These boundaries are not determined through an optimization analysis and therefore need a continued examination [24].

2.1.1 Electrification Planning Theory

Electrification planning models are built on the basis of algorithms and several mathematical concepts used to solve some of the problems associated with the infrastructure development of electricity networks in areas of interest. Graph theory is one underlying concept used in the configuration and optimization of electrical system distribution networks [25]. Montoya and Ramirez [26] define graph theory as a graph (*G*) referring to a set or collection of nodes or vertices and edges that connect pairs of nodes. The set of vertices and set of edges in graph G are normally represented as V (*G*) and E (*G*) respectively, while the number of vertices and edges in graph G are denoted by υ (G) and ε (G). Graphical representation of graphs is ideal and helps in the understanding of several of their properties. The graph has a subset of vertices and edges referred to as sub-graphs [27]. A connected sub-graph of a connected graph with all its vertices without cycles is known as a tree (acyclic connected graph) [26]. According to Ravadanegh et al. [28], one of the oldest and most basic problems in theoretical computer science is the minimal spanning tree problem. Currently, two greedy algorithms, Kruskal's and Prim's algorithms are used. These two algorithms are among those that serve in determining the minimum spanning tree which is crucial in achieving optimum system performance conditions in electrical system distribution networks.

Kruskal's algorithm is based on the generic minimum spanning tree algorithm. With Kruskal's algorithm, the edges are selected and connected to the spanning tree in increasing order, with respect to their weights, and an edge is added to the tree only if it does not form a cycle [26].

Kruskal's algorithm can be illustrated as follows:

- Candidates: edges
- Solution: tree building
- Restriction: set of edges contains cycle
- Selection: Select an edge from pool of candidates with less weight
- Objective function: determine the total minimum length of selected edges

Montoya and Ramirez [26] present Kruskal's algorithm pseudocode as follows:

```
function Kruskal ($G = \langle N, A \rangle$: $graph$; $length$: $A \rightarrow R^{+}$): $set\ of\ edges$
Define an elementary cluster $C(v) \leftarrow \{v\}$
Initialize a priority queue Q to contain all edges in G, using the weight as keys.
Define a forest $T \leftarrow \emptyset$
//$T$ will ultimately contain the edges of the minimum spanning tree
//$n$ is the total number of vertices
while $T$ has fewer than $n - 1$ edges do
//$edge$ $(u, v)$ is the minimum weighted route from $u$ to $v$
$(u, v) \leftarrow Q.removeMin()$
// prevent cycles in $T$. add $(u, v)$ only if $T$ does not already contain a path between $u$ and $v$.
```

```
        //The vertices have been added to the tree.
        Let $C(v)$ be the cluster containing $v$ and let $C(u)$ be the cluster containing $u$.
        if $C(v) \neq C(u)$ then
            add edge $(v, u)$ to $T$
            Merge $C(v)$ and $C(u)$ into one cluster, that is union $C(v)$ and $C(u)$.
    return tree $T$
```

Prim's algorithm forms a step-by-step minimum spanning tree where at each step the graph (G) side will have a minimum weight and therefore connected to the minimum spanning tree that has been formed previously. By taking the edge with the smallest weight of the graph, Prim's algorithm finds the minimum crop of a connected graph where the edge is adjacent to the measured tree created and has no cycles [29]. Prim's algorithm is said to be mostly suitable for trees with the larger vertices as it will always find the minimum spanning tree. However, the found minimum spanning tree needs sorting first as it is not always unique [30, 31]. According to Ramadhan et al. [31], Prim's algorithm pseudocode is as follows:

```
Input: Undirected – weighted graph
Output: minimum spanning tree T
T← ∅
Example r is any point in V
U ← {r}
```

```
While $|U| < n$ do
Determine $u \in U$ and $v \in V - U$
So that sides (u, v) are between U and V-U
$T \leftarrow T \cup \{(u, v)\}$
$U \leftarrow U \cup \{v\}$
```

In general, if G is a weighted connected graph, the steps to obtain the minimum spanning tree using Prim's algorithm are as follows:

- T is empty
- A point is chosen randomly and the related side with minimum weight is selected and entered in T
- Choose sides (u, v) with minimum weight and side by side at T, but (u, v) do not form a cycle at T. add (u, v) to T
- Repeat the above steps n-2 times

In Prim's algorithm, the total number of steps in n-1 is the same as the number of sides with the spanning tree with n points. Output: minimum spanning tree T [29].

Another important algorithm used in electrification modelling tools is the Locality Sensitive Hashing (LSH). According to Adoni and Indyk [32], LSH is an algorithm that efficiently searches for the nearest neighbour vector among a collection of vectors where each vector has a fixed dimension. LSH algorithm helps in making complex lookups in becoming sub-linear in the size of the collection. The algorithm is based on the existence of LSH functions and it is as follows:

We let $\mathscr{H}$ be a set of hash functions mapping Rd to universe U.

For points p and q, choose a function that h from $\mathscr{H}$ uniformly at random

Analyse the probability that $h(p) = h(q)$

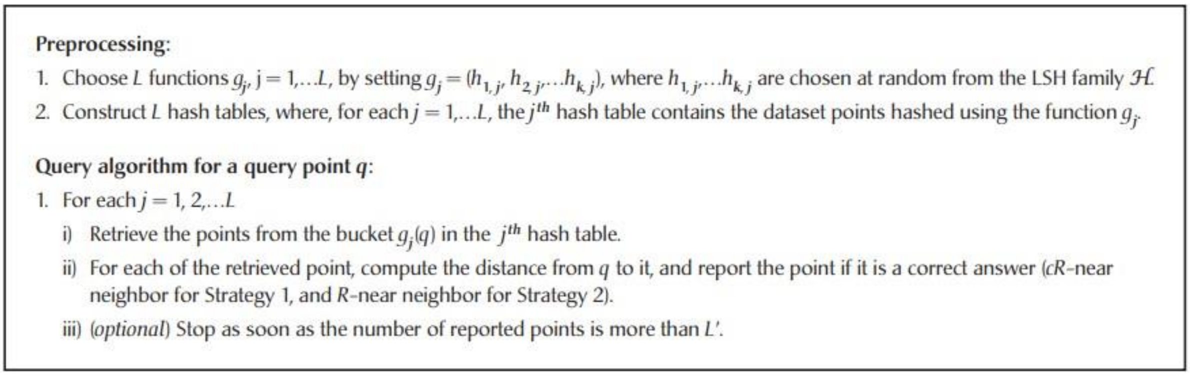
The set $\mathscr{H}$ is called locality sensitive if it satisfies the following condition:

A set $\mathscr{H}$ is called (R, cR, P_1, P_2)-sensitive if for any two points p, q $\in R^d$.

- If $||p-q|| \leq R$ then $\Pr_{\mathscr{H}}[h(q) = h(p)] \geq P_1$
- If $||p-q|| \geq cR$ then $\Pr_{\mathscr{H}}[h(q) = h(p) \leq P_2$

For LSH to be useful, it has to satisfy $P_1 > P_2$

Since P_1 and P_2 are probabilities, the gap between them could be really small thus $\mathscr{H}$ cannot be simply used. However, an amplification process illustrated in Figure 2 is needed to achieve the desired probabilities of collision.



Preprocessing:

1. Choose L functions g_j, j = 1,…L, by setting $g_j = (h_{1,j}, h_{2,j},\ldots h_{k,j})$, where $h_{1,j},\ldots h_{k,j}$ are chosen at random from the LSH family $\mathcal{H}$.
2. Construct L hash tables, where, for each $j = 1,\ldots L$, the j^{th} hash table contains the dataset points hashed using the function g_j.

Query algorithm for a query point q:

1. For each $j = 1, 2,\ldots L$
    - i) Retrieve the points from the bucket $g_j(q)$ in the j^{th} hash table.
    - ii) For each of the retrieved point, compute the distance from q to it, and report the point if it is a correct answer (cR-near neighbor for Strategy 1, and R-near neighbor for Strategy 2).
    - iii) (*optional*) Stop as soon as the number of reported points is more than L'.

Figure 2: Schematic of query and preprocessing algorithms of basic LSH algorithm [33]

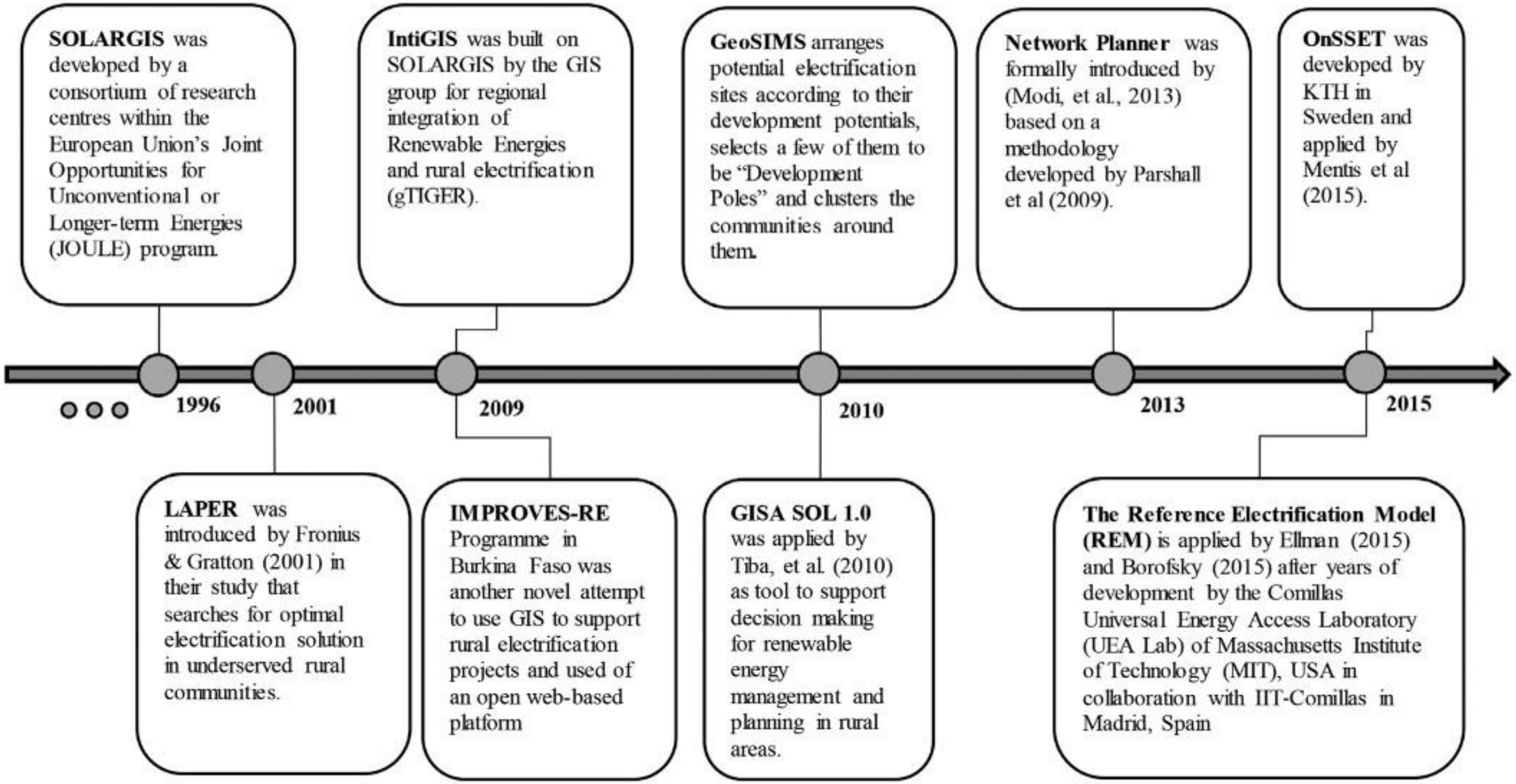
2.2 GIS-based Electrification Modelling Tools

Several GIS-based modelling tools are used for rural electrification planning and include OnSSET, Network Planner, SOLARGIS, IntiGIS, GeoSIMS, the Reference Electrification Model (REM), LAPER, IMPROVES-RE, and GISA SOL1.0, among others [11, 18, 26]. Figure 3 illustrates these models through their development by various researchers or groups and institutions to support decision-making in rural electrification and their usage time ranging from 1996 to around 2015 [11, 17]. A selection of these modelling tools is briefly reviewed and compared in the next sub-sections.

2.2.1 Network Planner

A Network Planner is an open-source GIS-based tool that provides a modelling framework for planning electricity infrastructure projects. This tool uses the modified version of Kruskal’s algorithm, also known as the minimum spanning tree; the algorithm finds the maximum length of medium voltage (MV) lines for which grid extension is cheaper than available off-grid technology options such as solar PV mini-grids and solar home systems [29,30]. It is usually used as a decision support tool in improving electricity access to rural communities by comparing long-term investment costs for electrifying communities through the installation of solar PV, diesel, or grid extension. The tool has several advantages including the fact that: a) it is available for free on the web, it has Google maps fully integrated with it and is thus advanced in spatial technologies; b) the tool is user-friendly and does not require in-depth knowledge of GIS and/or programming; c) the tool can easily be applied from a national level to subnation and the local levels [37].

In terms of geospatial data requirements, the Network Planner needs spatial location described by longitude and latitude; this is usually referred to as a node by the tool, which is the lowermost unit of the administrative area of the place that the study is being conducted for. Another important spatial data required is the infrastructure coverage of the existing transmission and distribution network in an area of interest. This data is needed as an ESRI shapefile [17]. The demographic data required includes the total population in demand of electricity within the node by the time of the investment, the population growth rate, the population distribution in terms of average household distance within the settlements to be electrified and the population threshold which is used to classify the node as either urban or rural area [38].



SOLARGIS was developed by a consortium of research centres within the European Union's Joint Opportunities for Unconventional or Longer-term Energies (JOULE) program.

LAPER was introduced by Fronius & Gratton (2001) in their study that searches for optimal electrification solution in underserved rural communities.

IntiGIS was built on SOLARGIS by the GIS group for regional integration of Renewable Energies and rural electrification (gTIGER).

IMPROVES-RE Programme in Burkina Faso was another novel attempt to use GIS to support rural electrification projects and used of an open web-based platform

GeoSIMS arranges potential electrification sites according to their development potentials, selects a few of them to be "Development Poles" and clusters the communities around them.

GISA SOL 1.0 was applied by Tiba, et al. (2010) as tool to support decision making for renewable energy management and planning in rural areas.

Network Planner was formally introduced by (Modi, et al., 2013) based on a methodology developed by Parshall et al (2009).

OnSSET was developed by KTH in Sweden and applied by Mentis et al (2015).

The Reference Electrification Model (REM) is applied by Ellman (2015) and Borofsky (2015) after years of development by the Comillas Universal Energy Access Laboratory (UEA Lab) of Massachusetts Institute of Technology (MIT), USA in collaboration with IIT-Comillas in Madrid, Spain

Figure 3: Timeline for different GIS-based electrification planning tools [17]

The Network Planner also requires data on economic variables such as the economic growth rate of the node, the scope of investment, the timeframe needed to improve the electricity access rate to a predefined level, income elasticity and the lending rate of the population to be electrified. Electricity demand for an area under study is also required by the tool. This includes household demand, institutional demand together with productive demand, among others [39]. Lastly, the tool requires detailed data on the costs for the electrifying technologies that the model considers, for the grid extension, mini-grid development and the installation of standalone systems. However, the tool does not consider biomass, hydro and wind as potential energy sources. This limits its application in areas that could rely on such resources.

Modi et al. [40] used the Network Planner tool to carry out a study focusing on the Liberian national electrification master plan which aimed to achieve electrification in the least-costly manner considering geospatial attributes. However, this tool does not take into consideration the detailed technical potential of renewable resources together with the administrative boundaries. Kamausour et al. [41] used the Network Planner to carry out an electrification planning analysis for Ghana where the study modelled electrification options for 2 600 communities. The study found that the most optimal option for the majority of these communities, based on cost, is the connection through the grid. The analysis estimated the total cost required to achieve universal access or 100% electrification rate to be around US$ 696 million with about 7 436 km of medium voltage and 6 926 km of low voltage lines required. Ohiare [42] also used the Network Planner tool to assess the expansion of electricity access to all in Nigeria by determining the least-cost electrification technology split between off-grid hybrid solar PV and diesel generator system, diesel generator mini-grid plant and grid extension. The study also assessed the estimated investment cost required for rural electrification in Nigeria. Despite Nigeria having vast of renewable resource that could be tapped into for electrification. The Network Planner limits the involvement in electrification options as it does not include some of these resources in the analysis.

2.2.2 SOLARGIS

SOLARGIS is one of the first electrification planning tools that integrated GIS. This tool was developed by a consortium of research institutions within the European Union’s Joint Opportunities for Unconventional or Long-term Energies (JOULE) programme, with the main objective being to demonstrate both the technological and economic viability and feasibility of applying GIS in the identification of the right technologies for improving electricity access in any region across the world [43]. This tool requires spatial data on the solar and wind resources availability and their potential at the place of study. The tool identifies the right electrifying technology solution for the unserved settlements by considering the levelized cost of electricity (LCOE) to meet the defined demand. This is done through two main options, the existing grid extension or the use of stand-alone systems [43, 44].

Concerning the stand-alone systems, the tool considers technologies such as solar PV systems with storage, including both the inverter and the batteries, solar PV systems without storage, small wind systems with storage and without storage, usually for water pumping, diesel generator sets for outlaying households and solar PV/wind hybrid systems [22,18,10]. On the contrary, with grid-extension the tool analyses the cost of the existing grid and the cost of new low voltage (LV) lines and connecting the MV/LV substations. This analysis is usually followed by a detailed comparison of different technologies for electrifying the area of study based on cost [46]. Notable studies carried out using this tool include Pinedo et al. [45] used SOLARGIS for the assessment of solar electrification in Cuba for rural development. The study applied SOLARGIS to compare the conventional and renewable energy technologies for all rural communities with no access to electricity found within the Guama municipality, east of Cuba. Monteiro et al. [47] evaluated electrification alternatives in developing countries study using the SOLARGIS tool. The main study objective was to develop a methodology and a tool enabling the identification of the most appropriate and adequate electrification technologies to be adopted in six chosen regions across the world and also to assess such electrification technologies economic feasibility in these areas. Amador and Dominguez [37] used SOLARGIS tool for the analysis of the application of geographical information systems to rural electrification with renewable energy sources in Lorca, Spain. The study introduced a proposal to improve the SOLARGIS including how the demand should be treated to improve optimization, the sizing of the centralized systems and the inclusion of some economic parameters and the grid calculations as the outcomes of the model are based on levelized electricity cost.

2.2.3 Reference Electrification Model

The Reference Electrification Model (REM) is designed and developed by a partnership between the Comillas UEA Lab of MIT in the United States of America and IIT-Comillas in Spain [48]. Its main objective is to assist in the electrification planning for unserved areas, especially large rural areas, to improve electricity access. It does this by identifying the least cost electrification technology solution for electrifying a given unserved area. This may be done through the grid extension, development of standalone systems, and/or mini-grid systems [49]. It is a static model that considers one future year and this makes it produce systems designs and installation costs estimate based on the demand for just that year. To estimate a lifetime performance of a system, REM takes into consideration the year-to-year effects in a simplified way. Compared to other electrification planning models, REM has quite high spatial granularity that can provide system design and cost estimation for an individual end user [50]. Regarding the spatial data requirement, REM utilizes data on electricity demand for the area under study on top of the data required by the Network Planner tool described above. This data is usually based on the type of customer and the demand pattern in the area. The type of customer depends on whether it is a household or commercial building whereas the demand patterns are defined in terms of hourly power consumption for either critical or non-critical demand in a year.

One downside of the model is that for mini-grids and standalone systems, it does not require wind and hydro resources data. Moreover, regarding grid extension and off-grid systems, the model requires information on the lowest acceptable levels [18, 20]. Despite these drawbacks and others, the reference electrification model has been used for several electrification studies across the world. Amatya et al. [48] used the Reference Electrification Model in computeraided electrification planning in developing countries. The study argues that REM represents the state of the art in modern GIS-based electrification planning tools as it takes full advantage of the geospatial data and information and it also works at the maximum granularity level in time and space.

Ciller et al. [39], is a study about optimal electrification planning incorporating on- and offgrid technologies using the Reference electrification model. The study also supports the argument that REM stands apart from other tools which work as it does because of its high granularity and because it can provide clear electrification plans for a wide range of geographic scales. In a study by Ciller et al. [51], an optimization methodology by reference electrification model that calculates the generation costs of any potential off-grid system in a large-scale rural electrification planning scenario, maintaining a balance between accuracy and computational speed is introduced. The methodology introduced two procedures intended to mitigate the impact of the components with discrete behaviour on economies of scale. It was observed that the two procedures ensured that when connecting grouped end-users to large mini-grids, such mini-grids benefited from economies of scale. However, the study encountered two major limitations. Firstly, the study only considered solar PV and diesel generators for generation yet there are other resources such as wind, hydro and bioenergy. Secondly, demand profiles were crucial deterministic input parameters yet there was much uncertainty regarding demand profiles in developing countries, suggesting that this issue should be addressed in depth before undertaking a study of this nature.

2.2.4 OnSSET/GEP

OnSSET is computer software developed by a consortium of different institutions such as KTH Royal Institution of Technology and Energy System Analysis Group in Sweden, with the funding bodies being the World Bank, UNDP, and IEA among others [9, 13]. This tool determines the least-cost effective electrification technology solutions in electrifying areas or communities that are currently unserved while also taking into consideration the investment costs that will be needed to implement projects that will deliver sustainable access to electricity. According to Korkovelos [52], the global electrification platform (GEP), which is built on the bases of OnSSET's functionalities and characteristics, is an open, inclusive and scalable stage or platform that facilitates open access to many data layers and customizable modelling solutions associated with electrification planning.

The idea behind GEP is to improve spatial literacy regarding energy access and to facilitate better policy and decision-making in an attempt to deliver SDG7 [53]. The primary objective of GEP is to promote openness and transparency through enabling reusability, reproducibility and replicability of data and processes embedded in GEP. Figure 4 depicts the structural ecosystem of the GEP, detailing the three-level approach of the GEP explorer, the GEP generator and the GEP toolbox. The GEP explorer provides electrification investment outlooks that are openly accessible and up-to-date for different scenarios. The GEP generator is an opensource user interface used for electrification investment, outlooks generation and additional customization while the GEP toolbox facilitates open access to both input and output data together with the tools used in the generation of outlooks and documentation, including training materials.

To achieve the least cost electrification, the model objectifies the least cost options for electricity generation and supply technologies from solar home systems and stand-alone systems to grid extension and even different generation mixes. It also objectifies the investment that will be required to provide the most cost-effective solution for electricity infrastructure development to provide the unserved communities with electricity [54]. According to Isihak et al. [17], this is possible because the model applies geospatial information such as infrastructure, resources and topology to demographic, socio-economic and energy demand together with their projections through linear programming techniques. This modelling tool uses the tree search algorithm that traverses iteratively through the un-electrified settlements or the so-called sub-set of the tree nodes. This is done using Locality-Sensitive Hashing (LSH) algorithm to identify the most suitable and optimal electrification option [11].

OnSSET requires several data sets to model electrification planning. Such data sets include the basic data required by most of the GIS-based electrification modelling tools already described above. In addition, it requires administrative boundaries of where the study is being conducted, road networks, nighttime lights, distribution transformers, land covers and raster data sets for renewable energy resources to be used for generating power from wind, solar and hydro, as depicted in Table 1. Since one of the model's targets is to aid and support the achievement of SDG7, it has been used in several studies across the world. For example, in Nigeria, Isihak et al. [17] assessed the evolution of GIS-based rural electrification planning models together with the application of OnSSET in Kaduna State. This indicates that solar PV mini-grid is the least-cost electrification technology option for the majority of un-electrified communities and that the total investment required by the Kaduna State to achieve 100% electrification by 2030 was estimated at around US$505.08 million. For this State to achieve universal access to electricity, an additional generation capacity of around 252 MW was required.

Mentis et al. [9] carried out a study illustrating the application of OnSSET in Sub-Saharan Africa (SSA). The study mapped and calculated the electrification options for about 25.8 million locations in SSA. Such electrification option includes grid connections, mini-grid connections and stand-alone options. This is done through developing a bottom-up cost optimal method that describes the electrification technology mixes to meet different demand profiles for electricity in SSA. According to the study, demand profiles, population density and distribution play a crucial role in electrification technology selection. Furthermore, the study estimated the minimum total investment needed to achieve universal access to electricity in SSA by 2030 to be around US$50 billion while the maximum investment for 100% electrification in SSA by 2030 was estimated to be around US$1.3 trillion. The study concluded that OnSSET serves as a complementary approach for energy planning models that came before it and does not consider geographical attributes related to energy and electricity specifically.

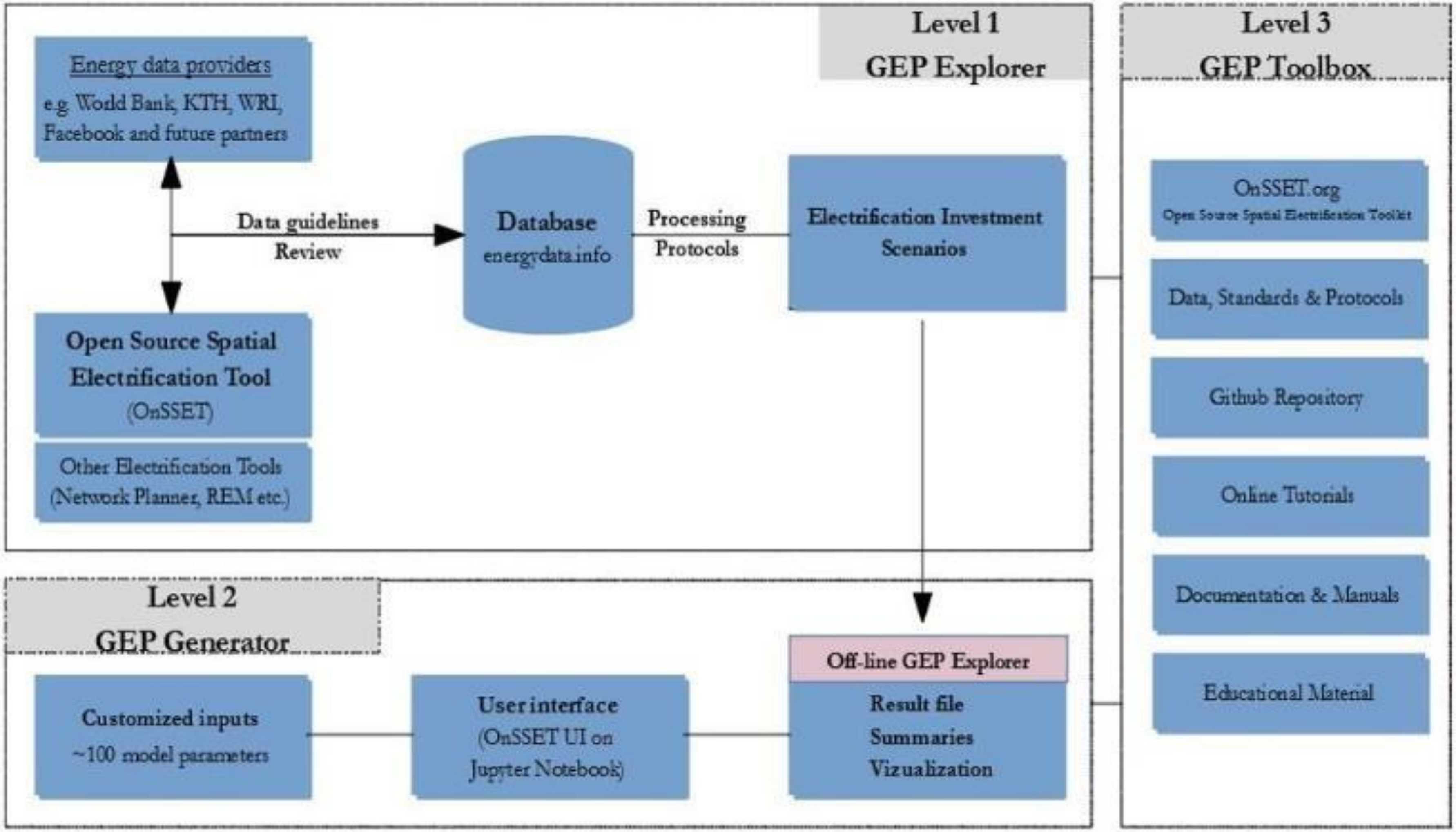


Figure 4: Global Electrification Platform ecosystem structure (Adopted from [52])

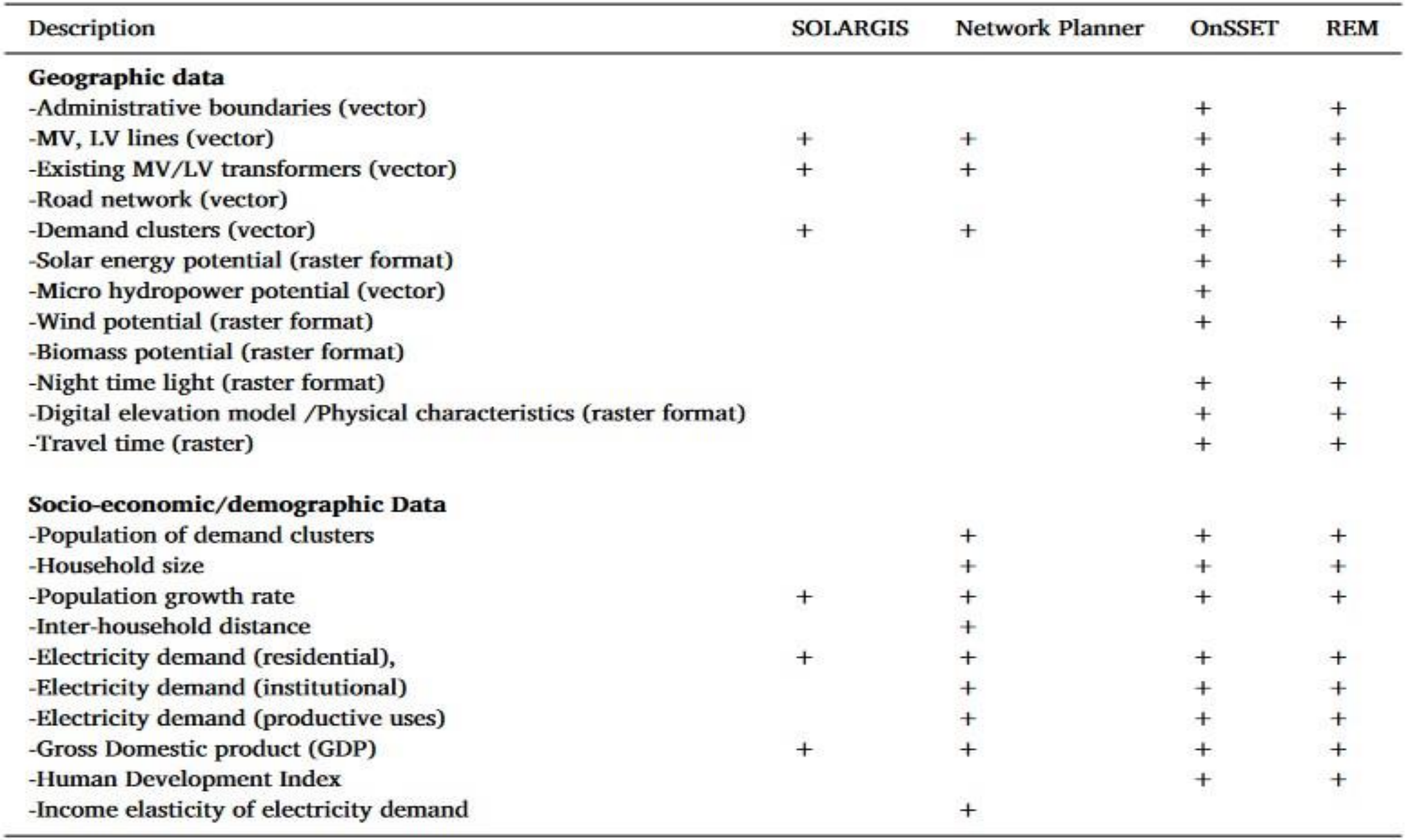
Korkovelos et al. [11] carried out a study to assess the role of open-access data in geospatial electrification planning for Malawi. The study introduced and used an updated version of OnSSET (OnSSET-2018) for the analysis scenario developed for Malawi. The analysis yielded an estimate of US$1.83 billion for the investment needed to achieve universal access to electricity in the base scenario. It was also observed that off-grid solar PV technologies are the least-cost electrification technology options connecting the majority of people in Malawi (67.4%). About 32.6% of Malawi's population can be connected through grid extension by the year 2030 according to the study. From the sensitivity analysis performed, it is observed that the electricity demand profiles impact both the electrification technology split and the total electrification investments required.

This study uses the OnSSET/GEP to model rural electrification for Lesotho; based on the data requirements, the software requires to produce clear and concise results that can be used in policy-making decisions. It also makes it possible to identify the best least-cost collection of electrifying options available for the rural areas in Lesotho from the grid extension to off-grid options such as stand-alone and mini-grid systems, considering all available resources. In addition to information regarding data requirements by different GIS-based electrification planning tools described in Table 1, the study opted for OnSSET because, unlike other tools. The tool considers all the renewable energy resources available. Moreover, the OnSSET model was built to support SDG7.

2.3 GIS Data Categorization

The basic GIS data types used in OnSSET electrification planning modelling are spatial data and attribute data. Spatial data mainly describes the size, location and shape of different objects. This type of data can be represented as either vector or raster data. As shown in Figure 5, vector data represents real earthly objects and their features such as roads, rivers and power plants transmission and distribution lines. This data has discrete boundaries and it is defined by specific coordinates, along with attributes. It is differentiated into three types namely, points, lines and polygons. Points are normally single vertex described by coordinates and attributes and thus apply to features that are too small to be displayed at the current scale or features without area. Lines are features consisting of at least two or more vertices connected. They have length but not an area and they describe some attributes. Polygons, on the other hand, form closed areas. The main difference between polygons and lines is that they consist of at least four vertices and the last and first vertex always shares the same coordinates.

Table 1: Data requirement comparison for different electrification modelling tools [17]



Description	SOLARGIS	Network Planner	OnSSET	REM
Geographic data				
-Administrative boundaries (vector)			+	+
-MV, LV lines (vector)	+	+	+	+
-Existing MV/LV transformers (vector)	+	+	+	+
-Road network (vector)			+	+
-Demand clusters (vector)	+	+	+	+
-Solar energy potential (raster format)			+	+
-Micro hydropower potential (vector)			+	
-Wind potential (raster format)			+	+
-Biomass potential (raster format)				
-Night time light (raster format)			+	+
-Digital elevation model /Physical characteristics (raster format)			+	+
-Travel time (raster)			+	+
Socio-economic/demographic Data				
-Population of demand clusters		+	+	+
-Household size		+	+	+
-Population growth rate	+	+	+	+
-Inter-household distance		+		
-Electricity demand (residential),	+	+	+	+
-Electricity demand (institutional)		+	+	+
-Electricity demand (productive uses)		+	+	+
-Gross Domestic product (GDP)	+	+	+	+
-Human Development Index			+	+
-Income elasticity of electricity demand		+		

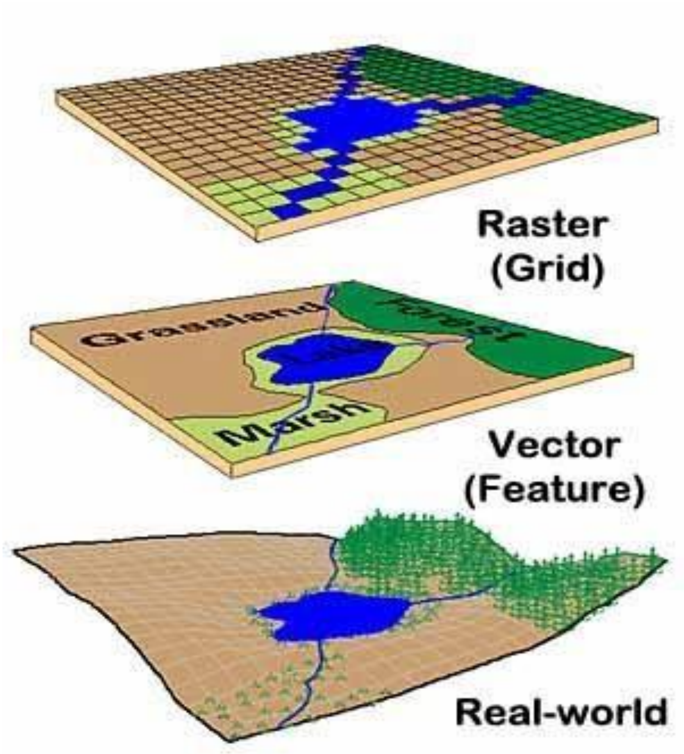


Figure 5: Geographic information system data types [55]

Raster data is mainly composed of cells forming matrices which together represent surfaces. It does not represent real-life objects with clear boundaries. In a matrix, every cell has its data stored in the form of attributes and coordinates, thus making raster data a good option for representing continuous surfaces across a larger area. This type of data has three different groups: Thematic, Continuous and Imagery groups. Thematic rasters represent datasets such as land cover which usually have sharp borders while continuous rasters represent datasets such as temperature, elevation slope and wind speed all of which are data that tend to lack sharp borders. Imagery rasters are scanned maps that commonly represent base maps. They are usually used to ensure that the vertices in the vector datasets are correctly aligned. Raster data is used for a wide range of applications from base maps underneath the vectors in order to validate and give them contexts to being used as surface maps for purposes of effective way of storing the continuity as a surface and /or as thematic maps usually used for classifying surfaces into different classes, depending on attributes of choice.

2.4 Research Gap Analysis

In the context of Lesotho, GIS-based electrification has not yet been explored in fine detail. Mentis et al. [9] assessed electrification analysis using OnSSET at the SSA regional level; the GEP online site [53] also developed electrification and investment scenarios for several countries, including Lesotho. However, this study attempts to use OnSSET/GEP considering the latest GIS data and filling gaps in data where possible to develop comprehensive GIS-based electrification scenarios considering the business-as-usual scenario and to analyse how certain parameters affect the selection of the least-cost electrification technology mix and investments required to achieve a 100% electrification rate in Lesotho by 2030 as a way of supporting SDG7.

3. Materials and Methods

3.1 OnSSET Modelling

The procedural steps to be followed in this study when modelling with OnSSET, are summarized successively as illustrated in Figure 6, where the first step is to collect and process data. The required data consists of a variety of spatial data that usually comes as vector or raster data as well as non-spatial data. The collected spatial data is inclusive of a) infrastructure consisting of transmission and distribution network, sub-stations and transformers, power plants and road network, b) energy resources such as solar, wind, hydro and biomass, and c) socio-economic variables such as a poverty map, settlement distribution, income level and productivity activities. Other layers may include nighttime light, land cover, travel time and biomass. The non-spatial or attribute data include input parameters such as electrification rate, urbanization rate, population growth rate, household size, technology cost, technical specification, demand level and target, fuel prices, policies, etc., as illustrated in Appendix. Appendix A shows a list of variables used for generation and electrification scenario for Lesotho.

Secondly, data is transformed through the validation of collected information according to standards and calibration of geospatial information with national statistics. There is also additional processing and/or generation of derivative layers followed by the projection of socio-economic indicators and preparation of model input data and files. The third step is to configure the geospatial modelling framework. This involves model selection and configuration followed by defining the optimization type and decision parameters. This study uses the OnSSET plugin installed on QGIS and the GEP generator. Then there is scenario selection, configuration and of defining the output type or format. The last step involves analysis/sensitivity and associated results, where the main results are in comma separated values (CSV) file format and can be uploaded into the quantum geographic information system (QGIS) as a delimited text layer to produce interactive relevant maps enabling improved visualization.

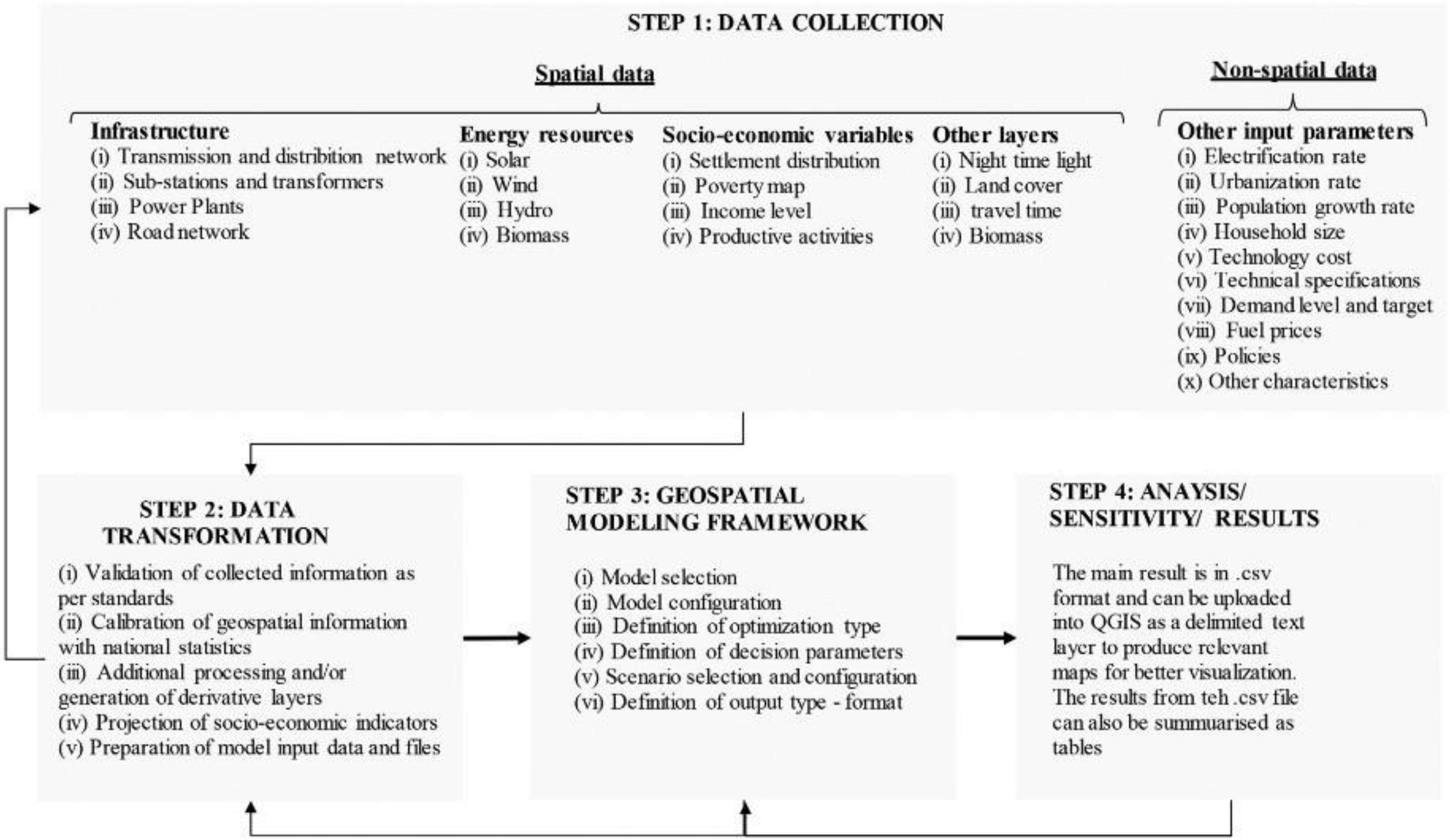
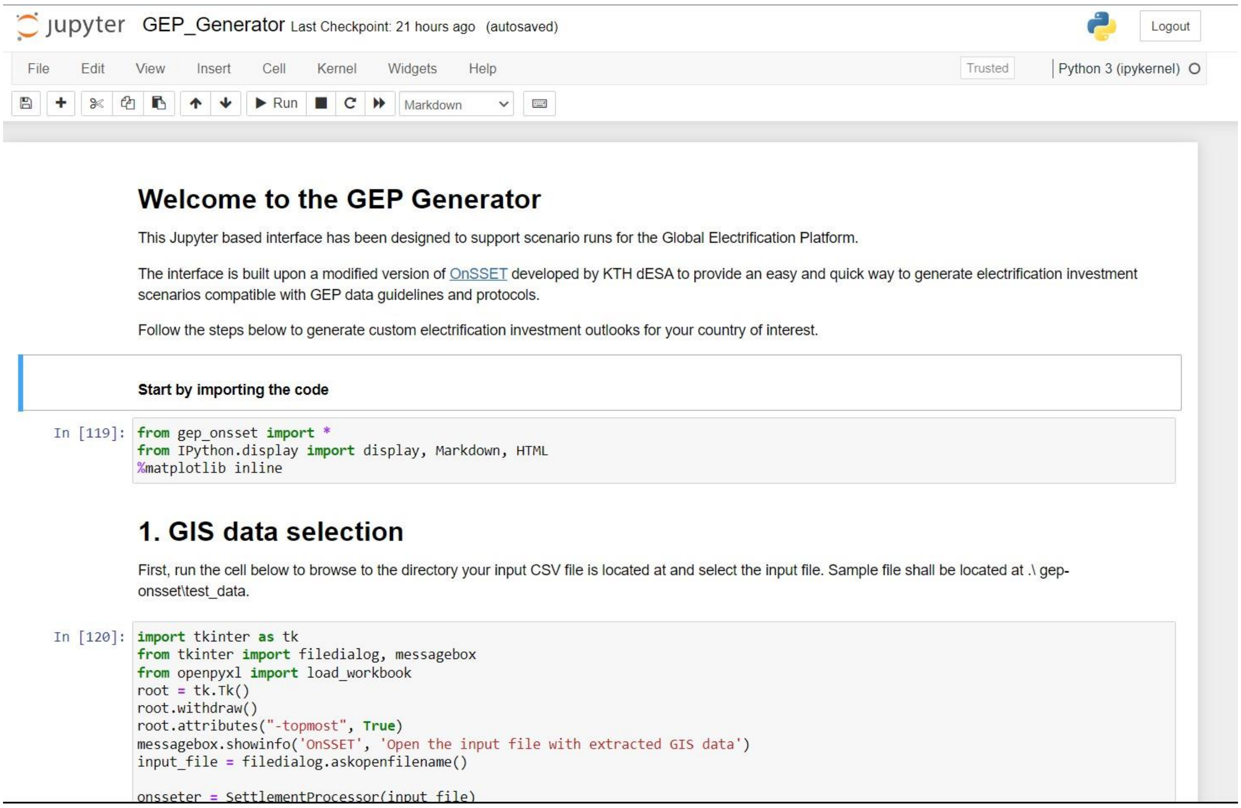


Figure 6: Schematic of OnSSET modelling procedure [11]

After acquiring the .csv files, the OnSSET python codes are run through a python-integrated development environment such as Jupiter notebook where an interface was developed to aid and support scenario running for the GEP. In the GEP generator (Jupiter notebook) as shown in Figure 7, the code is imported and then the .csv file obtained in the previous steps is uploaded and the non-spatial data imputted. This step produces another .csv file with many columns of relevant results. It is this file, as illustrated in Figure 8, that when uploaded onto QGIS again produces maps and visuals that are easier to interpret.



Welcome to the GEP Generator

This Jupyter based interface has been designed to support scenario runs for the Global Electrification Platform.

The interface is built upon a modified version of OnSSET developed by KTH dESA to provide an easy and quick way to generate electrification investment scenarios compatible with GEP data guidelines and protocols.

Follow the steps below to generate custom electrification investment outlooks for your country of interest.

Start by importing the code

In [119]:

```
from gep_onsset import *
from IPython.display import display, Markdown, HTML
%matplotlib inline
```

1. GIS data selection

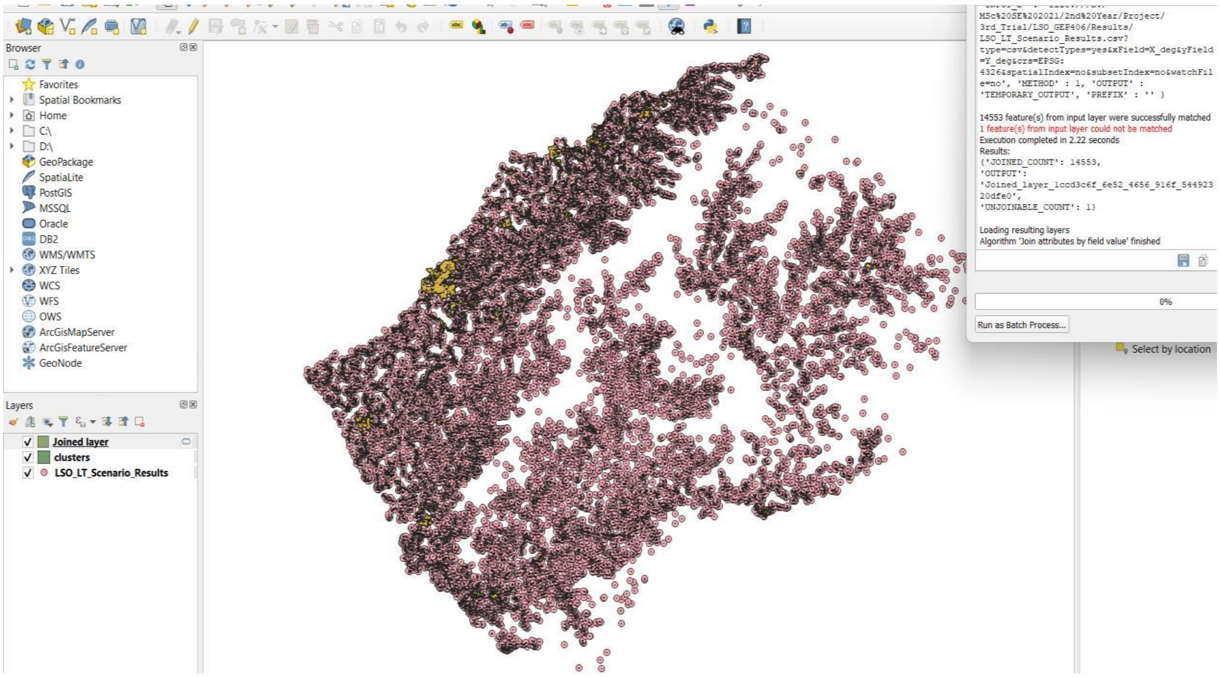
First, run the cell below to browse to the directory your input CSV file is located at and select the input file. Sample file shall be located at .\ gep-onsset\test_data.

In [120]:

```
import tkinter as tk
from tkinter import filedialog, messagebox
from openpyxl import load_workbook
root = tk.Tk()
root.withdraw()
root.attributes("-topmost", True)
messagebox.showinfo('OnSSET', 'Open the input file with extracted GIS data')
input_file = filedialog.askopenfilename()

onsseter = SettlementProcessor(input_file)
```

Figure 7: The snapshot of the GEP generator interface from the Jupiter Notebook (Adopted from the OnSSET/GEP tool)



```
MSc%20SE%202021/2nd%20Year/Project/
3rd_Trial/LSO_GEP406/Results/
LSO_LT_Scenario_Results.csv?
type=csv&detectTypes=yes&xField=X_deg&yField
=Y_deg&crs=EPSG:
4326&spatialIndex=no&subsetIndex=no&watchFil
e=no', 'METHOD' : 1, 'OUTPUT' :
'TEMPORARY_OUTPUT', 'PREFIX' : '' }

14553 feature(s) from input layer were successfully matched
1 feature(s) from input layer could not be matched
Execution completed in 2.22 seconds
Results:
{'JOINED_COUNT': 14553,
'OUTPUT':
'Joined_layer_1ccd3c6f_6e52_4656_916f_544923
20dfe0',
'UNJOINABLE_COUNT': 1}

Loading resulting layers
Algorithm 'Join attributes by field value' finished
```

Figure 8: Snapshot of scenario output file generated from the GEP generator when uploaded in QGIS

3.2 Step 1: Open Access Data Preparation

GIS-based electrification planning tools rely heavily on the availability of reliable datasets to model with precision and thereafter provide solutions and scenarios almost similar to the reality on the ground. In recent years, the quality and reliability of open-access GIS datasets that are publicly available have improved significantly [11]. .

Table 2 summarizes GIS datasets that are required for modelling with OnSSET. Such datasets provide highly regarded information including resource availability, up-to-date demographics and social and economic characteristics of different areas at global, regional and countryspecific levels. The following sub-topics discuss some of the crucial datasets essential in GISbased electrification planning with a specific focus on Lesotho as the area of study.

Table 2: Summary of GIS datasets required for modelling with OnSSET

#	Dataset	Type
1	Administrative boundaries	Raster
2	Population and distribution	Raster
3	Existing grid network	Line shapefile
4	Substations	Point shapefile
5	Power plants	Point shapefile
6	Roads	Line shapefile
7	Hydropower points	Point shapefile
8	Planned grid network	Line shapefile
9	Land cover	Raster
10	Elevation map	Raster
11	Slope	Raster
12	GHI	Raster
13	Wind speed	Raster
14	Travel time	Raster
15	Night time lights	Raster
16	Poverty map	Raster

3.2.1 Lesotho's Population Density and Distribution

The total population of Lesotho is estimated to be 2 142 249 as of 2020 and is estimated to rise to around 2 325 164 by 2030. It occupies a total land area of 30 360 km^2 [56]. This population is distributed across the entire country from the lowlands to the foothills and the Senqu Valley and the highlands, with the lowlands and some part of the foothills making up the urban areas while the highlands, the Senqu Valley and some parts of the foothills make up the rural areas. The urban population makes up 31.5 % of the total population while the rural population makes up 68.5% [57]. However, as shown in Figure 9, the urban population density (people/km^2) is much higher than that in the rural areas. For example, both Leribe and Berea districts have more than 100 residents per km making their population densities 117.1 and 123.2 respectively. Butha-Buthe, Maseru and Mafeteng follow as the districts with the most people per unit area. Rural districts such as Mokhotlong, Thaba-Tseka and Qacha's Nek are less densified with an average density of around 26 to 30 residents per km^2.

Figure 9: Lesotho's population densities by districts [58]

Figure 10, on the other hand, illustrates the distribution and the densities of people in Lesotho per grid cell at a resolution of 3 arc seconds. It can be observed that the urban areas in Lesotho, especially the city center in Maseru, have the highest number of people per grid cell. Along the blue mountain range, there are few or no people in some grid cells. The rural areas have the lowest number of people per grid cell.

The population data file is represented by the population cluster shapefile obtained from Khavari [59]. Such a file is composed of several attributes defining different settlement characteristics including size and number of households, location of a settlement, and population per such settlement among others. For Lesotho, the files publicly available lacked most of the attribute data, and to fill such data gaps, QGIS was used and the reclassification and the clusters were done by adopting a methodology by Korkovelos et al. [11].

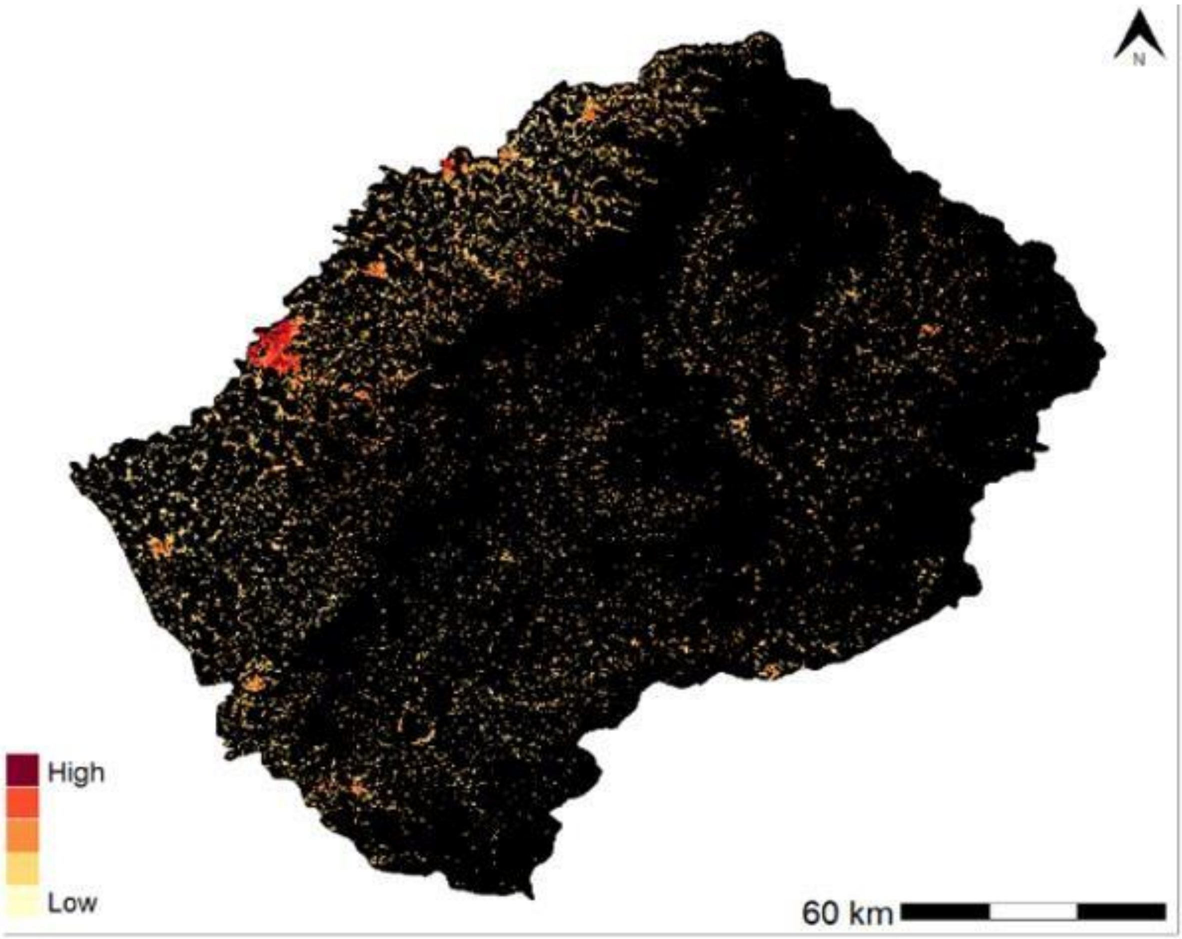


Figure 10: Estimated relative distribution of people per grid cell at a resolution of 3 arc seconds

3.2.2 Night Time Lights

Nighttime lights are satellite imagery of the earth's surface displaying captured light sources across the globe. Different sources are used to provide nighttime lights as they are good in assessing electrified households within a settlement or a region of interest through light pollution. There are data sets, such as Earth Observatory, which make night-time light data available at different spatial resolutions. However, it does not provide stable light composites [60]. There is also a Visible Infrared Imaging Radiometer Suite (VIIRS) data set which provides a spatial resolution of about 250 m, VIIRS defines low luminosity with low value within a given cell and vice versa. VIIRS data is used in this study to estimate the night time light intensity for Lesotho. As illustrated in Figure 11, most places, especially the rural areas such as those in Mokhotlong, Thaba-Tseka, Qacha’s Nek and Quthing, have night time light intensity of 0, where only the town centres of these districts show some light intensities. Moreover, large parts of Mohale’s Hoek, Butha-Buthe and Mafeteng also do not show any night time lights. On the other hand, most areas in Leribe, Berea, and Maseru districts show higher night time light intensities. The pattern of night time lights in Lesotho follows the national grid network, as shown in Figure 12, thus indicating that most places along the grid network are electrified. The night time lights play a crucial part in estimating the electrification status at the beginning of the modelling period when using OnSSET/GEP.

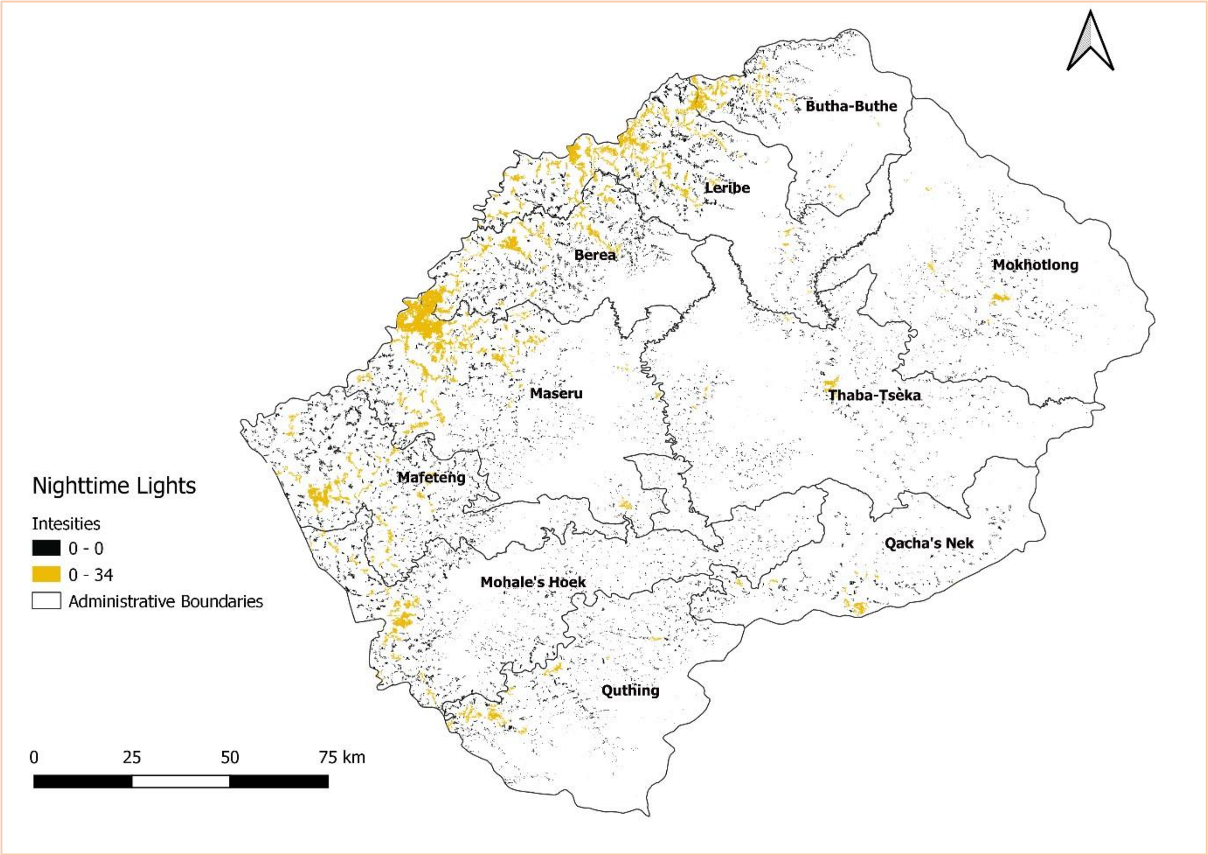


Figure 11: Nigh time lights for Lesotho [61]

3.2.3 Lesotho's Current Electricity Infrastructure and Electrification Status

According to a recent report by Lesotho's DoE [62], only about 51% of the total population has access to modern electricity and among those with access to electricity, 87% reside in urban areas. In the rural areas the electrification rate is 11%. Mpholo et al. [23] forecasted the overall electrification to be 54.2% by the year 2030 and that rural electrification would have gone as far as 14% by the same year. This implies that as a country we are destined not to achieve SDG 7 by 2030 unless strategies that fast-track electrification planning and implementation are employed.

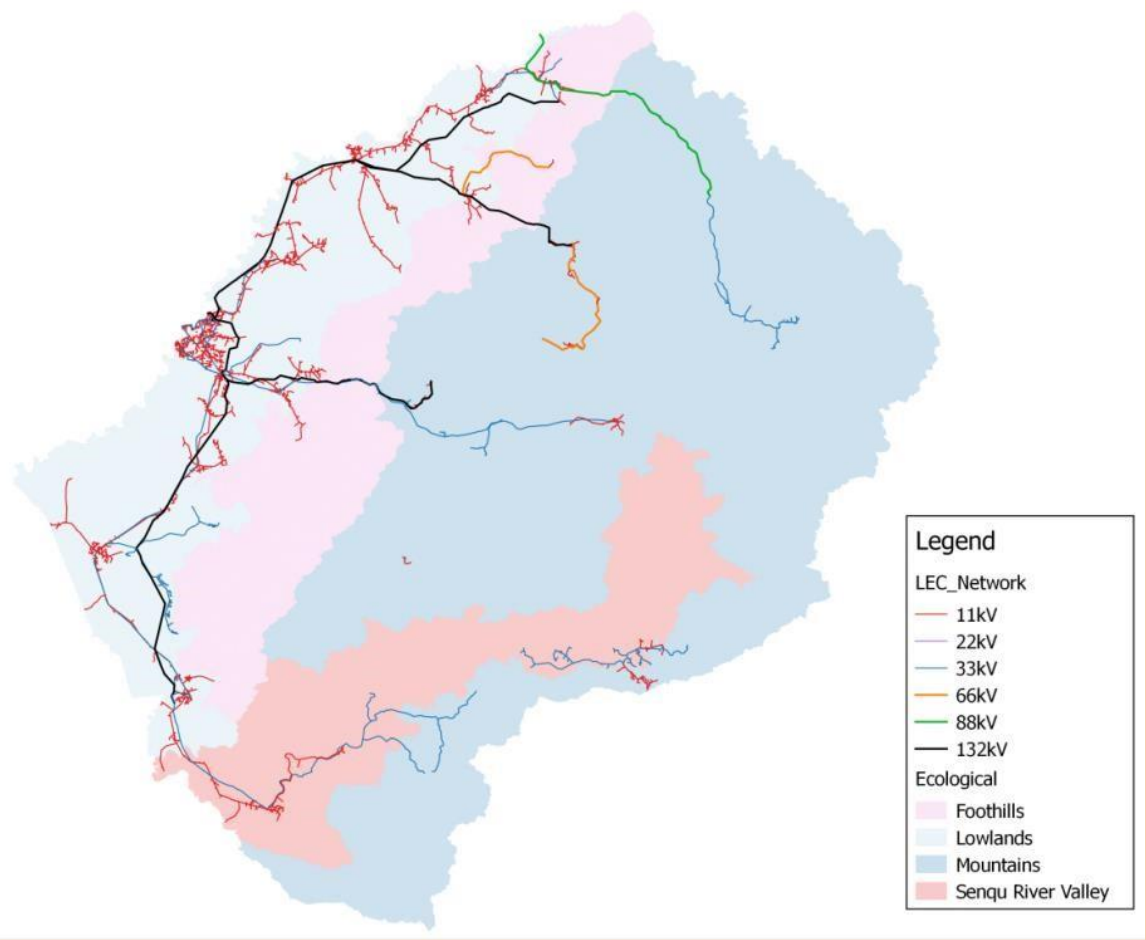


Figure 12: Existing national grid network [63]

LEC has several assets under its sleeves across the country, ranging from transmission and distribution lines and substations. The transmission lines operate at 132, 88, 66, and 33 kV even though LEC distributes at 33 kV in some places such as Thabana-Morena in Mafeteng [63]. The distribution lines, on the other hand, mainly operate at 11 and 0.24 kV and there are about 45 substations across the country. Figure 12 shows the existing transmission and distribution network in Lesotho and it can be observed that the grid is most concentrated in the lowlands where 11 kV lines are the most. The HV lines are run over the longest distances with the 132 kV line running from Butha-Buthe heading towards the south of the country, the 88 kV line carries the imported power from Clarens in South Africa through Butha-Buthe to Mokhotlong. Most of the MV lines run over considerable distances for transmission over close areas. However, publicly available shapefiles data representing this network have some gaps. For example, the vector data sets representing both service transformers and planned transmission and distribution network are not publicly available. Furthermore, the existing transmission and distribution network data found at [64] does not include the 11 kV lines and substations. It represents the network only up to 2017. To try and fill some of these gaps within the transmission and distribution network, Figure 12 was used in QGIS to georeference the current network onto the already available transmission and distribution shapefile for Lesotho.

3.2.4 Resource Availability and Mapping

Decentralized electrifying options usually rely on the availability of resources such as solar irradiance and wind for solar photovoltaic modules and wind turbines respectively, because these are of significance as they determine the long-term sustainability of electrification [7, 11, 30, 31]. Currently, unserved areas in Lesotho, which are mostly in the rural areas, can be better served with PV systems and or wind power systems provided that the resources are available rather than serving them with diesel generators or extending the grid to such areas. Earthorbiting satellites can capture and map different resource availability onto all regions across the globe. This enables scientific researchers to assess and analyse such resources at different levels [67].

In Lesotho, D’lsidoro et al. [68] estimated the solar and wind energy resources for Lesotho using the Weather Research and Forecasting (WRF) tool. The study observed that Lesotho generally has a good solar PV potential as solar resources spread with low variability throughout the country. As depicted in Figure 13, the highlands show higher solar PV potentials than the lowlands as they mostly have around 1700 to 1850 kWh/kWp. On the other hand, wind power resources with adequate potential to generate power are only found in distinct areas mainly towards the south and eastern parts of the country, as shown in Figure 14. The highlands consist mainly of the rural communities that are largely unserved with electricity at the moment. With such available resources, a well-orchestrated rural electrification planning can support SDG 7.

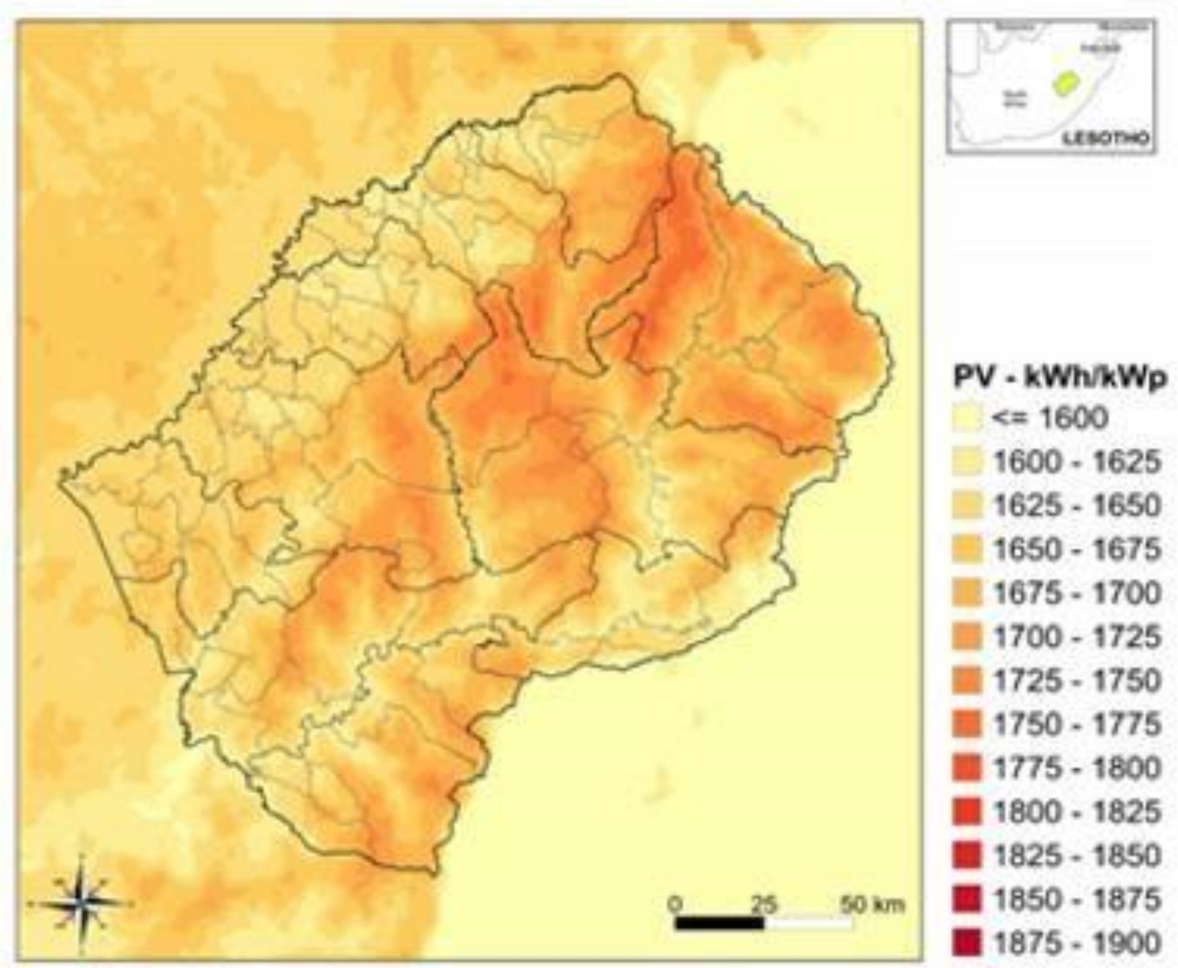


Figure 13: Yearly cumulated PV energy potential [68]

Lesotho is also rich in hydropower resources as it has several reservoirs and rivers flowing through and within it. Taele et al. [69] stated that the country has an economically viable hydropower potential of about 450 MW, considering the conventional systems of which only 72 MW have been exploited so far. There is also the potential of more than 3000 MW of pumped storage schemes. The 72 MW hydropower plant is by far the only sole producer of electricity that is locally fed into the grid. Besides these large hydropower schemes, there is also the potential for the development of small hydropower plants throughout the country. As illustrated in Figure 15, Lesotho has river systems including Senqu (Orange), Makhaleng, Mohokare, etc., which run mainly from north to south within the country, making them more economically viable for run-off river systems or mini-grid systems.

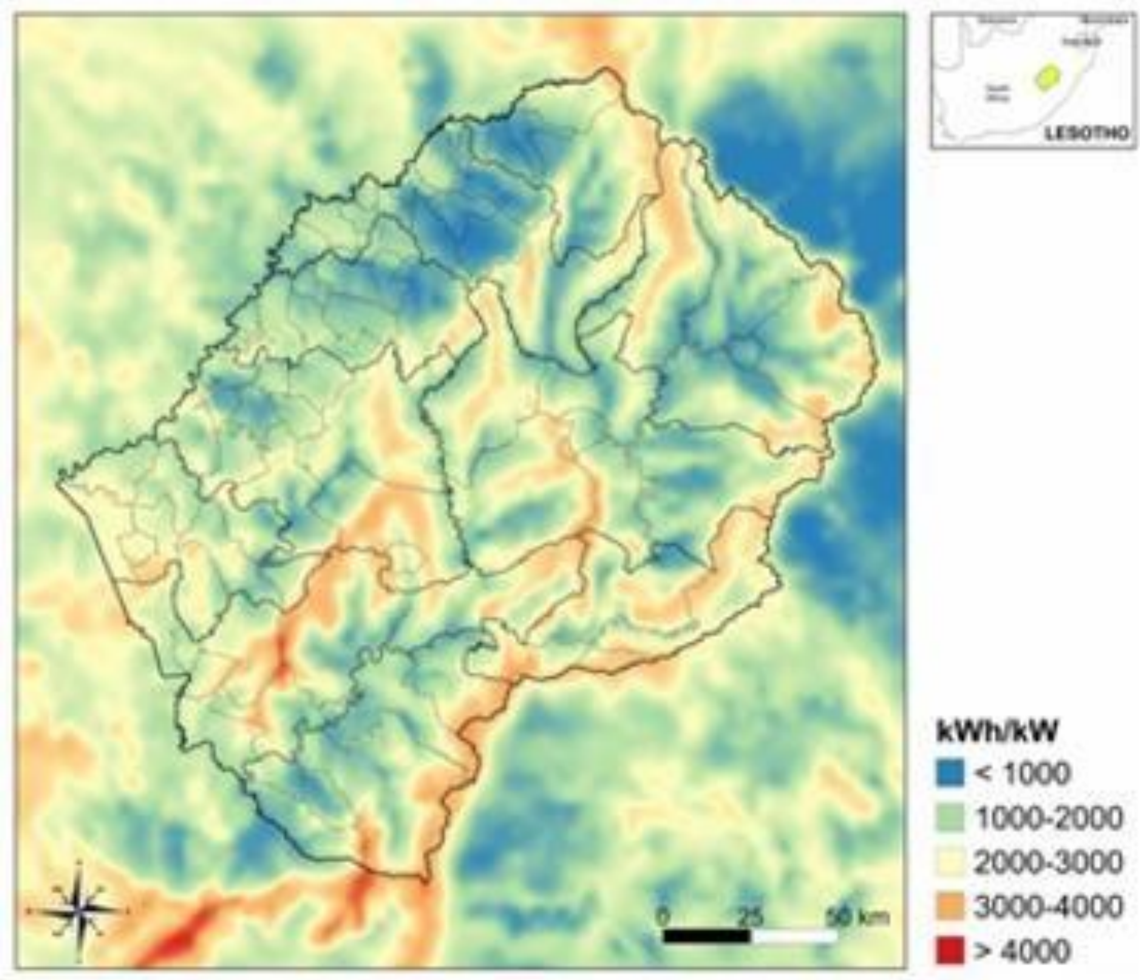


Figure 14: Normalized wind energy potential map for Lesotho [68]

There are currently about four small/micro hydropower plants, namely the Mantsonyane 2 MW plant, Semonkong hybrid (180 kW hydro and 120 kVA diesel), Tlokoeng hydro-diesel hybrid (670 kW hydro and 200 kVA diesel) and the Tsoelike hydro-diesel hybrid (400 kW hydro and 520 kVA diesel). There are also other identified areas for the development of small and large hydropower plants across the country, mainly by LHDA, such as Oxbow and Metolong [70]. In QGIS, solar and wind potential raster files from global solar and wind atlases were used while for the hydropower potential, an African hydropower point's shapefile was used.

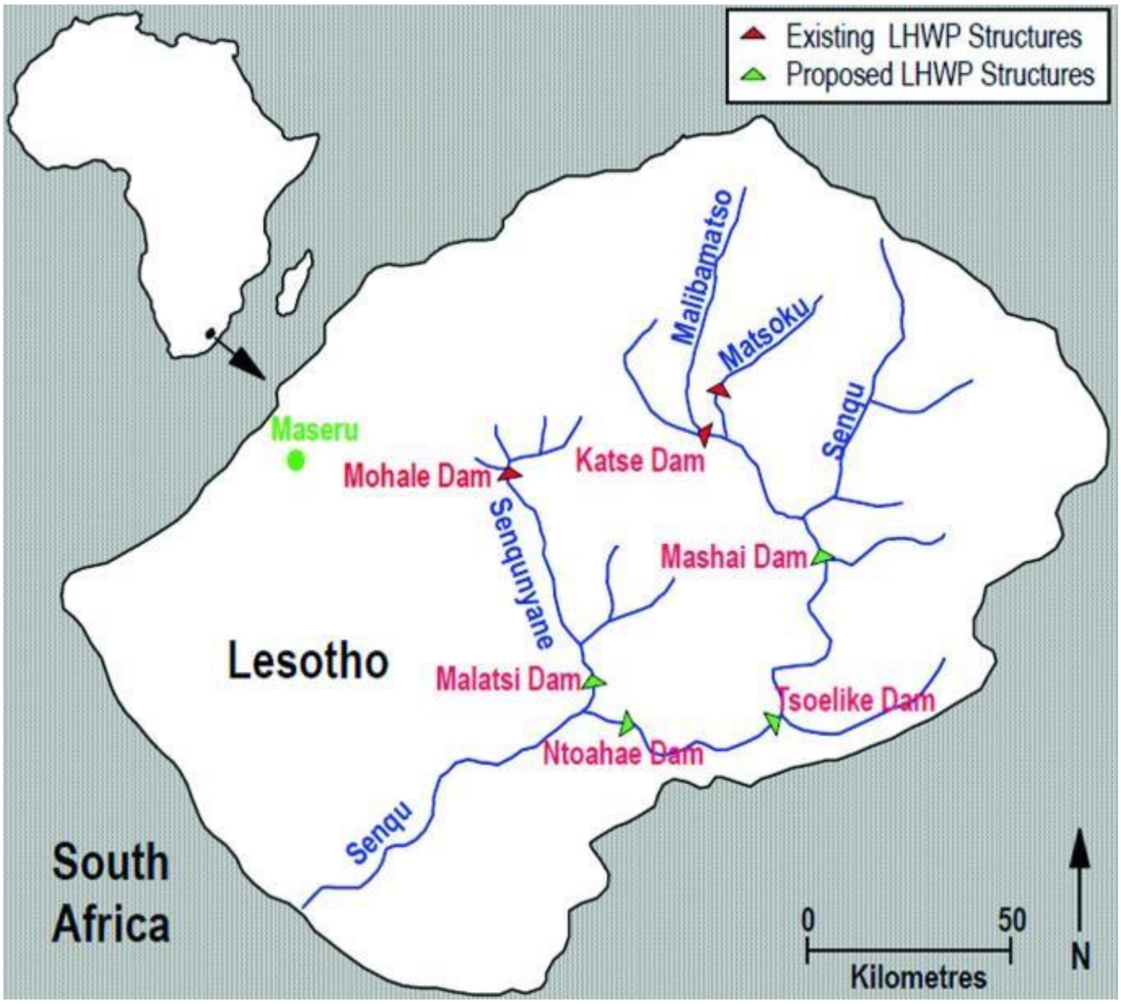


Figure 15: Existing and potential hydropower points and river networks in Lesotho [70]

3.3 Step 2: OnSSET/GEP Data Transformation

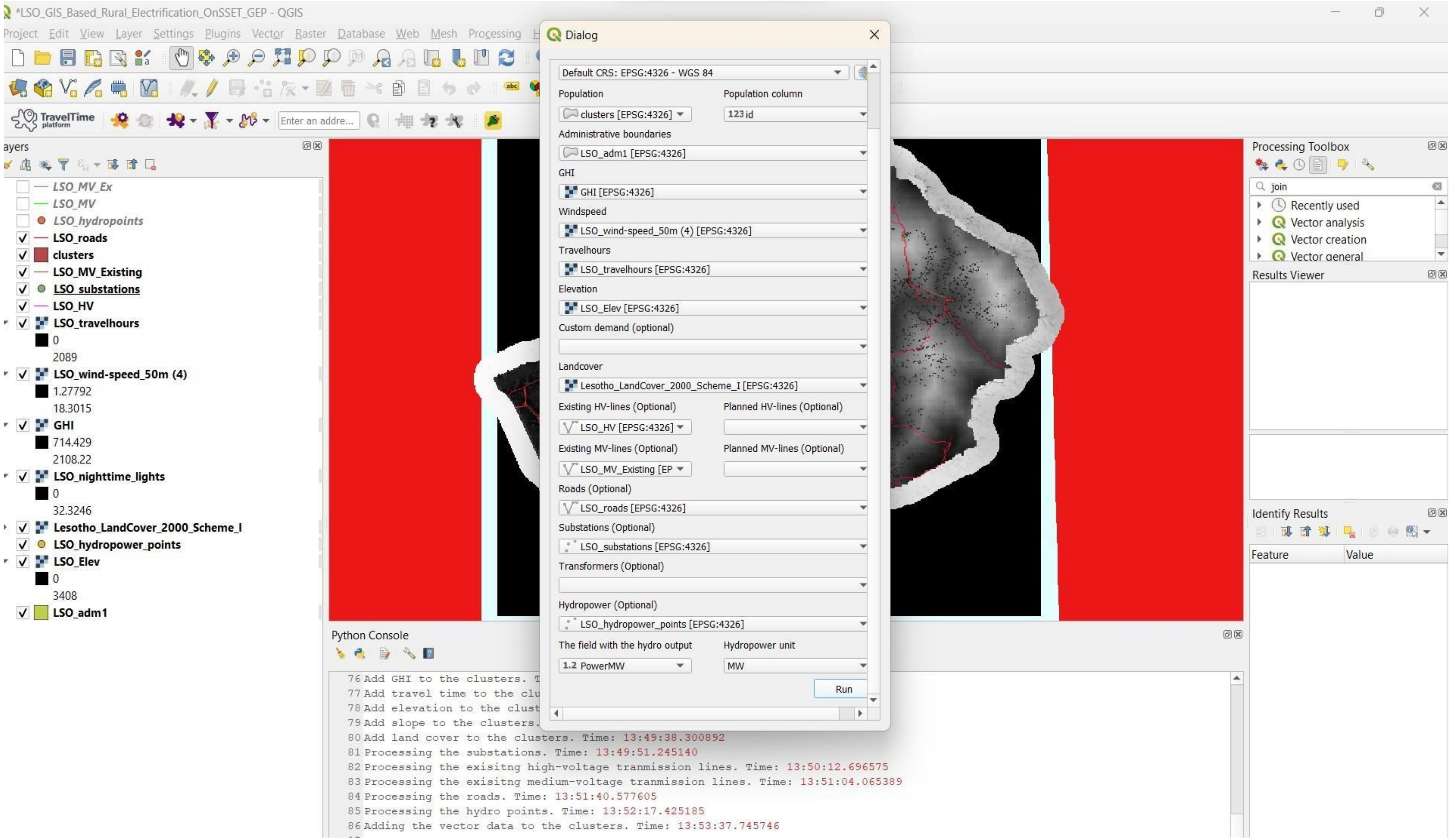
3.3.1 Data extraction to comma-separated values (CSV) file

This step is done using the QGIS software where the OnSSET QGIS plug-in developed by the KTH-dES is installed. The plug-in requires the datasets shown in .

Table 2 to be uploaded in QGIS and to make sure that such datasets have the correct type with an accurate coordinate system for Lesotho. Once the datasets are successfully uploaded in QGIS, an empty folder, named Lesotho to serve as a workspace, is created. The OnSSET plugin is, thereafter, opened and the pop-up requires the following information and datasets:

workplace and the name of the study area, target CRS, population, administrative boundaries, GHI, wind speed, travel hours, elevation, custom demand, land cover, existing and planned HV and MV lines, roads, substations service transformers, hydropower with hydro output and hydropower unit.

Figure 16 outlines the datasets input for this study in the OnSSET plug-in.



Default CRS: EPSG:4326 - WGS 84

Population: clusters [EPSG:4326]

Population column: 123 id

Administrative boundaries: LSO_adm1 [EPSG:4326]

GHI: GHI [EPSG:4326]

Windspeed: LSO_wind-speed_50m (4) [EPSG:4326]

Travelhours: LSO_travelhours [EPSG:4326]

Elevation: LSO_Elev [EPSG:4326]

Custom demand (optional):

Landcover: Lesotho_LandCover_2000_Scheme_I [EPSG:4326]

Existing HV-lines (Optional): LSO_HV [EPSG:4326]

Planned HV-lines (Optional):

Existing MV-lines (Optional): LSO_MV_Existing [EP

Planned MV-lines (Optional):

Roads (Optional): LSO_roads [EPSG:4326]

Substations (Optional): LSO_substations [EPSG:4326]

Transformers (Optional):

Hydropower (Optional): LSO_hydropower_points [EPSG:4326]

The field with the hydro output: 1.2 PowerMW

Hydropower unit: MW

```
Add GHI to the clusters. T
Add travel time to the clu
Add elevation to the clust
Add slope to the clusters.
Add land cover to the clusters. Time: 13:49:38.300892
Processing the substations. Time: 13:49:51.245140
Processing the exisitng high-voltage tranmission lines. Time: 13:50:12.696575
Processing the exisitng medium-voltage tranmission lines. Time: 13:51:04.065389
Processing the roads. Time: 13:51:40.577605
Processing the hydro points. Time: 13:52:17.425185
Adding the vector data to the clusters. Time: 13:53:37.745746
```

Figure 16: QGIS snapshot with the OnSSET plug-in running

Once all the boxes from the OnSSET pop-up have the correct data, the plug-in can run. The progress of this process is displayed in a Python console. When the plug-in has finished running, the finish message is displayed on the Python console window. The whole process produces a CSV file in the workspace folder; such a CSV file is then used in the electrification analysis step outlined below, making use of the GEP scenario generator.

3.3.2 Electrification Analysis Using GEP Scenario Generator

The GEP scenario generator runs the electrification analysis using the Jupiter Notebook. This step requires that the Anaconda/python and the OnSSET package are pre-installed. A folder named gep-onsset-1.1 is obtained from the GEP-OnSSET GitHub page. This folder contains all the code necessary for running the electrification analysis. Data acquisition and insertion of such data into the electrification model is the next procedure. The first required data is the GIS data prepared in Subsection 3.3.1. This is imported by running the cell to browse and find where the file is located. The file is then selected. This step is followed by choosing the modelling period, the start year, the intermediate year and the end year and the target electrification rate for both the intermediate year and the end year. The programme then moves onto the levers section where different variables such as the end-year population projection and electrification prioritization are entered.

Table 3: Preview of imported GIS data as per this study

	Country	Pop	NightLights	TravelHours	GHI	WindVel	Hydropower	HydropowerDist
1609	Lesotho	1609.0	0.000000	20.650000	2013.049663	4.785193	194.258	48.988167
13302	Lesotho	13302.0	0.000000	2.983333	2021.731680	3.408984	202.782	7.699437
9964	Lesotho	9964.0	0.218214	1.616667	2076.619282	5.016541	278.180	54.273448
453	Lesotho	453.0	0.249234	4.336292	2066.341146	2.794886	72000.000	6.669194
2790	Lesotho	2790.0	0.000000	1.050000	2077.605668	3.406792	278.180	40.342531
4837	Lesotho	4837.0	0.000000	16.166667	2042.113037	3.390910	194.258	80.997162
13534	Lesotho	13534.0	0.000000	18.333333	1949.669854	2.943044	212.968	24.035935

In addition to the levers, country-specific data including the variables that describe the economic, social, political and technological environment are customized to depict the current state of the country or an area of study. The next step is to import and process the GIS data. This allows the calibration of the population and other (additional) basic information based on the GIS data to allow the tool to configure electrification scenarios. Table 3 shows the preview of Lesotho’s GIS data imported into the GEP generator. The preview illustrates each population cluster with its related characteristics. For example, a population cluster with a total population estimate of 9 964 people has night time lights intensity of 0.218214, travel hours of 1.616667, GHI of 2076.619282 W/m^2, wind speed of 5.016541 m/s at 50 m elevation and hydropower capacity of 278.180 kW, among other important information.

Using the imported and processed GIS data provided in Table 3, the code is able to create additional layers to be used in the electrification analysis. The first step in doing so is to identify the already electrified settlement clusters, based on the following spatial attributes with each having a default threshold: a) distance of settlement from a service transformer, b) distance to MV lines, c) distance to HV lines, d) night-time light intensity, and e) population. Table 4 displays some of the default threshold values used in the GEP generator in the case of Lesotho.

Table 4: Default threshold values for Lesotho

Attribute	Default threshold
Distance to service transformer	< 1
Distance to MV lines	< 1
Distance to HV lines	< 3
Night-time light intensity	0
Population	50

3.4 Step 3: Geospatial Modelling Framework Configuration

According to Korkovelos [11], Distance to the service transformer is a priority variable for identifying electrified settlements but where it is unavailable or not adequate, distance to MV lines is a good alternative. Where the two are not available, distance to HV lines can be used. These three options need to be coupled with night-time light intensity and/ or population to minimize selecting and identifying un-electrified locations close to the transmission and distribution network as electrified. Therefore, an electrified settlement should have more nighttime lights than the threshold. It should be within the distance limit of the existing grid network and it should have more population than the default threshold. For Lesotho, the calibration of the current electrification resulted in an achieved electrification rate of 49.6% with urban electrification of 86% and rural electrification of 14%.

Next, the demand is defined and can be adjusted further into the scenario. According to the government of Lesotho 2015 energy policy and the Electrification master plan, the country goal is to provide every settlement in the country with at least minimum energy of around 38 kWh per year [63]. This is equivalent to the energy demand tier 1. Tier 2 equates to 219 kWh/ household/year, tier 3 equates to 803 kWh/household/year and tier 4 is equivalent to 2117 kWh/household/year. In this electrification analysis, tier 1 is set as a target for rural electrification while tier 4 is set as a target for urban areas.

The last step after configuring all the variables into the code is to run the scenario. This runs the algorithm to calculate the least cost technology to be used for electrification in every settlement in a country. In this analysis, the rollout plan option used is the forced grid approach where the buffer zone is well defined with auto intensification set to equal to 2 km and the least cost approach to be used outside the buffer zone. In order to extend the grid, the grid extension algorithm starts by sizing the transmission lines, either HV lines or MV lines. The first step is deciding on which type of line will be used to electrify a settlement cluster based on two parameters, grid distance and the peak load, as explained in

Equation 1.

$$Transmission_{linetype} = \{_{MV\,HV,,grid \quad distance \quad ot \leq hMV\,erwise}{}^{\max reac \quad h} \;|\;| \; peak \quad load \quad \leq \max \quad MV \quad load$$ Equation 1

where;

$$\text{Max MV\_load} = \text{MV}_{\text{type}} \times \text{MV}_{\text{amp\_limit}} \times \frac{HV\ cost}{MV\ cost}$$ Equation 2

$$\text{peak\_load} = \frac{(cluster\ electricity\ demand/(1-T\&D\ loasses))/8760}{Base\ to\ peak\ load\ ratio}$$ Equation 3

After determining the type of line to be used, the algorithm estimates the mileage for additional lines using the grid distance and the number of transmission lines needed.

The second step is to size service transformers (ST) and connection to substations. For each cluster to be electrified, the algorithm estimates the number of service transformers needed to fully provide coverage as per $\#\_\boldsymbol{of\_ST}$=

$$\max\{\frac{S_{max}}{ST\_type}, \frac{total\_nodes}{nodes\_per\_transformer_{max}}, \frac{clusters\ area}{transformer\_area\_coverage_{max}}\}$$ Equation **4**.

$$\#\_\boldsymbol{of\_ST} = \max\{\frac{S_{max}}{ST\_type}, \frac{total\_nodes}{nodes\_per\_transformer_{max}}, \frac{clusters\ area}{transformer\_area\_coverage_{max}}\}$$ Equation 4

where;

$peak\ load$

$S_{max} = power \underline{\qquad\qquad} factor$

Equation 5

$transformer\ area\ coverage_{max} = \Pi \times LV\ line\ length^{2}_{max}$ Equation 6

$total\ nodes = \frac{cluster\ population}{\#\ of\ people\ per\ household} + productive\ nodes$ Equation 7

The sum of all household loads connected to a service transformer is referred to as the transformer load and is defined by $transformer\ load = \frac{peak\ \ load}{\#\ of\ ST}$

Equation **8**.

To estimate a distance of a service transformer from a substation, an assumption that transformers are evenly spaced within a population cluster is made, thus the average transformer substation distance is 2/3 of the cluster's radius whereas the transformertransformer distance is twice the transformer radius.

$$transformer\ load = \frac{peak\ load}{\#\ of\ ST} \qquad \text{Equation 8}$$

The next step that the algorithm performs is to estimate the investment cost per cluster for grid extension and Equation 9 explains how the algorithm estimates the investment cost for extending grid per cluster, considering the transmission line cost, connection line costs, distribution line costs, substation costs and node connection costs.

$$grid\ extension_{per\ cluster} = (transmission\ line \times transmission\ line\ cost) + (connection_{linekm} \times connection\ line\ cost) + (distribution_{line} \times \frac{}{km}\ distribution\ line\ cost) + (substation\ type \times substation\ cost) + (\#\ of\ ST \times ST\ cost) + (total\ nodes \times node\ connection\ cost) \qquad \text{Equation 9}$$

Outside the buffer zone, the electrification technology used is primarily LCOE dependent. LCOE is the total cost of electricity required for a system to breakeven after its lifetime. The model selects the least costly technology to electrify the settlement clusters, assuming full

$\sum nt=-01\ I\underline{t}+(O1\&+Mr)\underline{t}t+F\underline{t}$

electrification by 2030. $LCOE = \sum_{n} t=-1 \underline{\ E_t\ } 0\ (1+r)t$

Equation **10** describes the LCOE as used by the algorithm. It is determined by a) population density as household per square kilometer, b) total electricity to be provided to both already electrified households and those that are yet to be electrified as kWh/household/year, c) locally available renewable energy resources and d) grid connection aspects and characteristics such as grid generation costs [71].

$$= \frac{+r)}{\sum_t^n \quad t \quad t} \qquad \sum nt=-01\ I\underline{t}+(O1\&M\underline{t}t+F\underline{t}$$

$$LCOE_{-1}\ \underline{E}$$

Equation 10

$$=0\ (1+r)$$

where;

I_t: investment expenditure for a specific system in year t
$O\&M$: the operation and maintenance costs

F_t: the fuel expenditure E_t:

the generated electricity r:

the discount rate n: the

lifetime of the system

3.5 Step 4: Sensitivity Analysis

The sensitivity analysis in this study considered three parameters, the demand, solar PV technology costs and population growth, used to generate four different scenarios that are compared and contrasted against the business-as-usual scenario (reference scenario) developed for this study. The first scenario looks into how higher demand affects the technology mix and investment estimates from 2020 to 2030. The scenario models for the demand between tier 3 and tier 5, are as defined by ESMAP multitier framework [72]. The second scenario still considers the demand but, this time around, it looks for the lowest demand with an access level between tier 1 and tier 4. The third scenario is based on the solar PV technology cost factor being reduced by 50% and the fourth and last scenario is based on a population growth rate higher by 2.5% from the reference scenario where it is 1.4% [73].

3.6 Visualization of Electrification Results

The electrification analysis process in the GEP scenario generator gives out three CSV files: results, summaries and key input variables. The results can easily be viewed as visuals using GIS software like QGIS, for example. The resulting CSV file gives a point layer in which the tool “join attributes by field value” can be used to visualize clusters used for the population layer to view the results. This procedure gives out a variety of maps displaying different information about the electrification analysis. These include different technologies best suitable for electrifying a settlement, investment cost and technologies with the least LCOE among others. Most of these results for Lesotho will be discussed in the next chapter.

4. OnSSET/GEP Simulation Results and Discussions

This chapter entails the main findings of the study, detailing how Lesotho can move from an electrification rate of 47.3% by 2020 to a 100% electrification rate by 2030 to attain universal access in line with SDG 7, using OnSSET/GEP considering geospatial, social and technoeconomic aspects under the business as usual conditions (reference scenario). This is followed by a sensitivity analysis carried out to see how electricity demand, solar PV cost, and population growth rate affect the least-cost electrification technology split and required investments. For the reference scenario, the calibration of the start year electrification status is discussed, followed by the electrification technology split, additional new capacity and the required investments that Lesotho needs to achieve universal access.

4.1 Calibration of the Start Year Electrification Status

The electrification analysis undertaken for Lesotho gave out several results. The simulation took 2020 as the start year with a national electrification rate of 47.3%, urban electrification rate being 88% and the rural electrification rate being 11%. Figure 17 outlines population clusters the model calibrated to be likely electrified at the start of the simulation. As illustrated, population clusters with blue colouring are assumed to be electrified while those in black colour are considered to yet be electrified as per the legend in Figure 17. This output shows that most electrified settlements are found in urban areas, especially in the lowlands part of the country, Leribe, Berea, Maseru and Mafeteng.

The 2020 electrification status also follows the current transmission and distribution network mapping as shown in Figure 12 and the population density map in Figure 9 where the model shows that places with high population density are probably electrified. When also considering the nighttime light intensity map in Figure 11, there is a clear correlation with this and it can be said with certainty that the model calibrated the start year electrification status with a high degree of correctness. The electrified settlements at the start of the simulation are all assumed to be electrified through a grid connection.

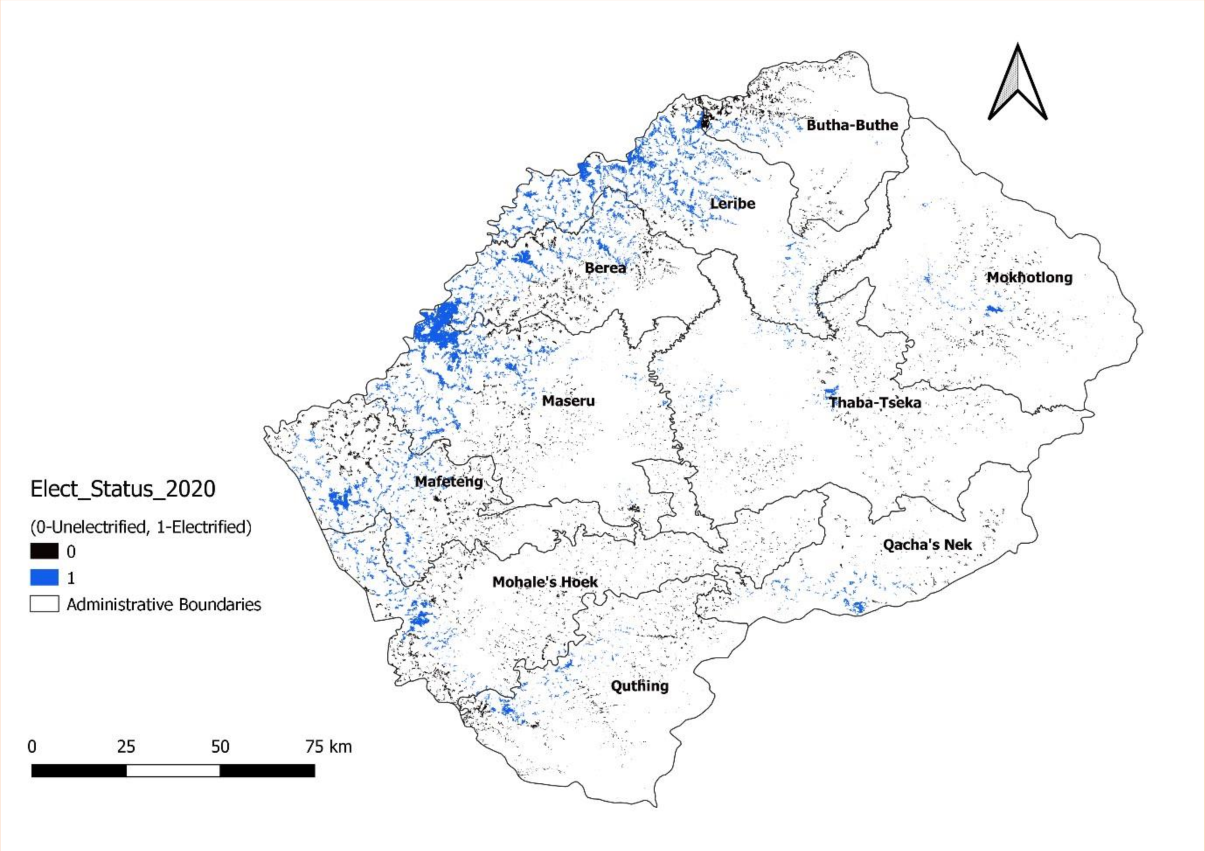


Figure 17: 2020 electrification status in Lesotho

4.2 Overall LCOE

OnSSET determines electrification outcomes based on the LCOE for a particular electrification technology. As illustrated in Figure 18, the analysis shows different LCOE calculations that determined the electrification options and investment costs for the reference scenario of this study. The LCOE differs from one electrification technology to another. For the grid technology, the LCOE represents both the cost of electricity generation on the grid and the transmission and distribution costs, while for off-grid systems, the LCOE represents total systems costs. A closer look at both Figure 18 and Figure 19 indicates that the LCOE for the grid technology is around 0.087 US$/kWh (the white colour on Figure 18 and red colour on Figure 19). The LCOE for both stand-alone and mini-grid systems are more (from 0.229 US$/kWh to around 0.8 US$/kWh) compared to the grid overall LCOE by 2030. These values resonate with projected costs of electricity for both grid and off-grid technologies. Highly remote and rugged areas such as those in Mokhotlong, Thaba-Tseka and Qacha’s Nek show high LCOE values (0.371 to 0.8 US$/kWh) whereas urban areas such as Maseru and Leribe mostly have low LCOE values (0.087 to 0.229 US$/kWh) because they are mostly electrified through the grid technology.

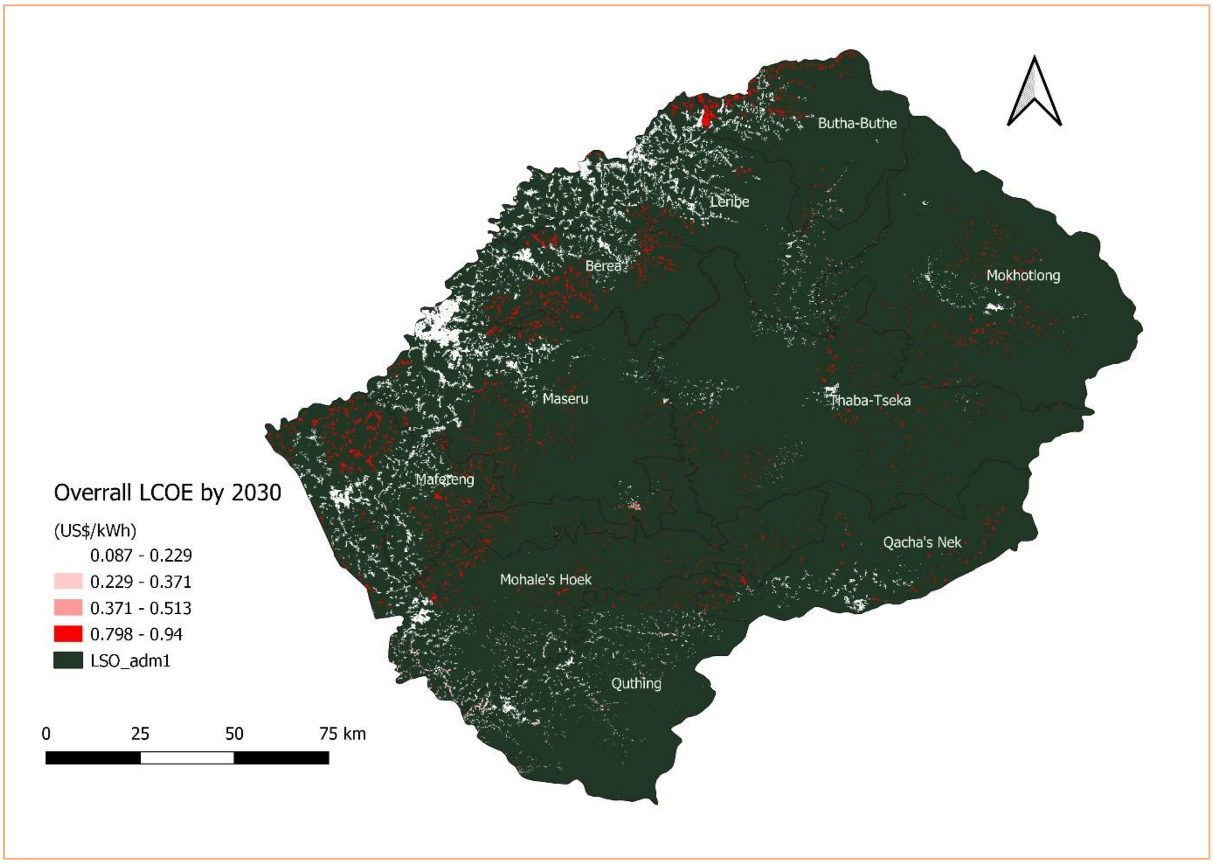


Figure 18: Overall LCOE for the reference scenario by 2030

4.3 Least-cost Electrification Technology Split for 2025 and 2030

According to the OnSSET/GEP model, considering the reference scenario where the start year has a total population of 2 142 249 people and the end year has a total of 2 325 164 people, the urban target tier level is 4 while the rural target tier level is 2. The solar PV cost adjustment factor is set at 1 and other levers as depicted in Appendix. Lesotho can reach a 100% electrification rate by the year 2030 using four different electrification technologies based on the least cost approach: grid, stand-alone PV systems, hydropower mini-grids, and wind power mini-grids.

By the intermediate year, 2025, Lesotho would have an electrification rate of 75.9%. This would be achieved through new connections of which grid extension accounts for 7.3% of all new connections by 2025. Most of the new grid connections are due to intensification within a buffer of 1.5 km of the already existing grid network. Stand-alone PV systems make up 91.4% of the majority of new connections achieved in 2025. The stand-alone PV system connections are observed across the country but mostly in the rural areas where the terrain makes such places hard to reach.

Furthermore, wind power mini-grids account for 1.1% of the new connections observed by 2025. Settlements connected to wind power mini-grids are generally located towards the southeastern parts of the country such as Mohale's Hoek, Quthing and small parts of Qacha's Nek. Lastly, hydropower mini-grids only account for 0.19% of new connections achieved by 2025. Some of these hydro mini-grids are found along the Senqu Valley, one in Mafeteng and the other in the Butha-Buthe district. On the other hand, the model did not include PV minigrids and the usage of diesel stand-alone and mini-grids was excluded in this reference scenario.

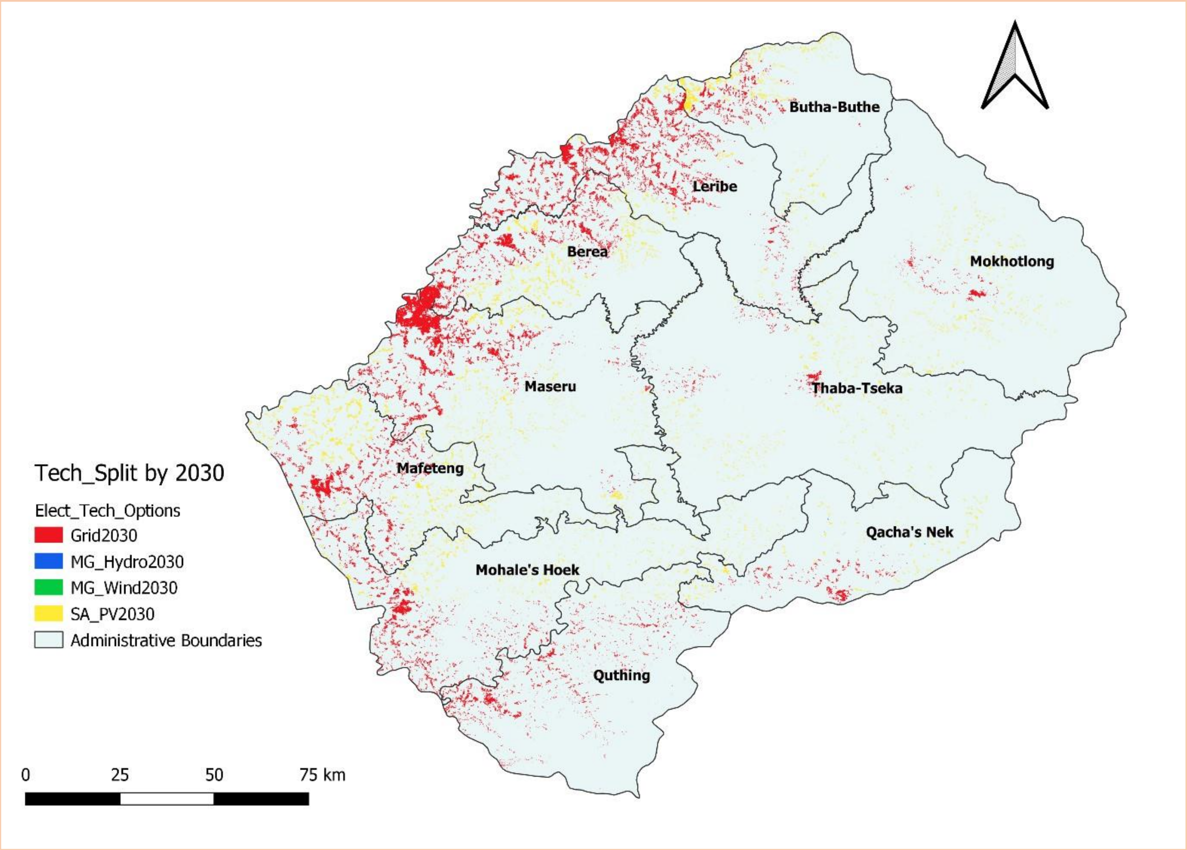


Figure 19: Electrification technology split by 2030 for the reference scenario

From the intermediate year (2025) to the analysis end year (2030), the grid connections account for most new connections at 90%. Stand-alone PV connections contribute about 9.7% of total connections in this period and hydropower mini-grids account for about 0.0068%. As seen in Figure 19, most of the new grid connections are mainly for the settlements found in lowlands and the areas surrounding the towns in the rural areas across the country. Leribe, Maseru, and Quthing stand out as the districts electrified mostly by grid while other districts such as Berea, Mafeteng, Mokhotlong and Thaba-Tseka are mostly electrified through off-grid technologies as per this reference scenario.

4.4 New Capacity in 2025 and 2030

To achieve the 75.9% electrification rate nationwide by 2025 from the 47.3% electrification rate in 2020, a total of about 25 MW capacity needs to be added to the already available capacity. Figure 20 shows how much capacity can be added to which parts of the country. It is observed that in the first five years of this simulation, districts such as Leribe, Mohale's Hoek, Quthing and Qacha's Nek need the least capacity of up to 0.0036 MW each. Butha-Buthe and Mafeteng districts, together with the south most part of Maseru only need a new added capacity of up to 0.96 MW for each of these regions. Berea and Mokhotlong districts need a new capacity of up to 3.47 MW while Maseru and Thaba-Tseka districts need the most of the new capacity. Each of these two districts needs a capacity of about 4.76 MW.

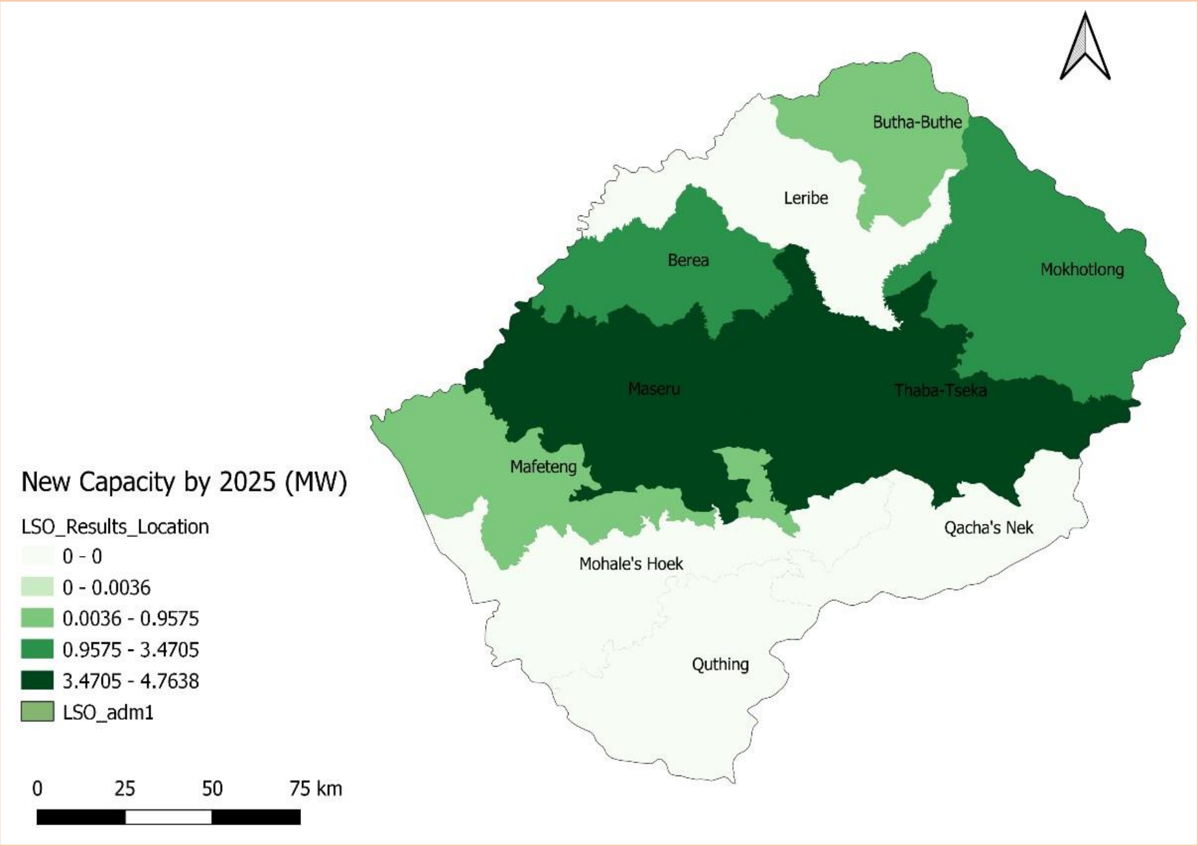


Figure 20: New capacity by 2025 for reference scenario

Of these new added generation capacities by the intermediate year, the stand-alone PV system generates the most, about 20 MW, and this is mainly because new connections within this time frame will mainly be through this technology. The grid only needs to increase generation capacity by 2 MW within the same time frame. The remaining 3 MW is split between the wind power mini-grid and hydropower mini-grid to complete the generation mix.

From the intermediate year to the end year, the simulated electrification rate moved from 75.9% to 100% nationwide. Figure 21 shows how an additional capacity of 40 MW is distributed across the country to attain a 100% electrification rate. Mafeteng and Butha-Buthe districts need the least additional capacity from at least 0.006 MW to 0.045 MW while Berea and Mokhotlong need a capacity of up to 0.082 MW. An additional capacity from 0.082 up to 0.975 MW is needed in each of the two districts, Maseru and Thaba-Tseka whereas in Mohale's Hoek and Leribe, a huge increase in additional capacity, up to 23.39 MW, is observed. Qacha's Nek and Quthing are the two districts that need the most additional capacity between 2025 and 2030, they each need between 23.39 and 41.69 MW.

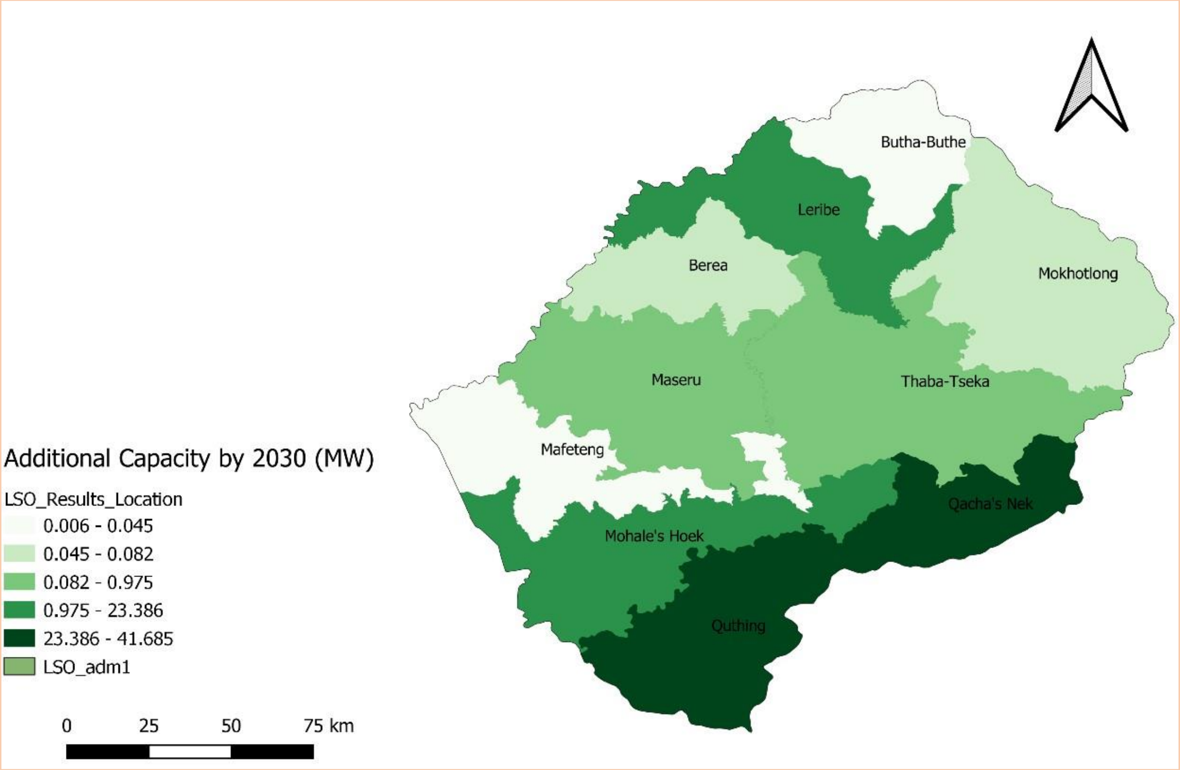


Figure 21: Additional capacity by 2030 for reference scenario

Most of the additional capacity between 2025 and 2030 is contributed through grid generation capacity increase, totaling 38 MW. Unlike in the first interval of the simulation period where it contributed most of the additional capacity, stand-alone PV systems only account for about 1 MW of the additional capacity this time around. Both the wind power mini-grids and hydropower mini-grids contribute less than 1 MW.

4.5 Required Investments in 2025 and 2030

Lesotho requires a total investment of US$401 million to achieve 100% electrification by 2030. This total investment is made up of US$156 million expected to push the electrification rate from 47.3% in 2020 to 75.9% by 2025 and US$245.5 million which will drive the electrification rate from 75.9% to 100% by 2030. Table 5 summarizes investments needed to achieve a 100% electrification rate in Lesotho by 2030.

Table 5: Investment cost per electrification technology for Lesotho from 2020 to 2030

Technology	**Total Investment in 2025 (US$ million)**	**Total Investment in 2030 (US$ million)**	**Total Investment 2020-2030 (US$ million)**
1. Grid	26.73	237.54	264.27
2. Stand-alone PV	127.51	7.31	134.82
3. Mini-grid Wind	1.59	0.68	2.27
4. Mini-grid Hydro	0.18	0	0.18
TOTAL	**156.01**	**245.53**	**401.54**

Looking at the period between the start year (2020) and the intermediate year (2025), grid expansion requires a total investment of around US$26.73 million, where about US$12.16 million is an investment towards new connections, US$11.77 million is recurring costs and about a total of US$9.03 million is an investment towards MV and LV transmission and distribution network expansion. Stand-alone PV systems need a total investment of around US$127.5 million within the same period. This investment solely goes into capacity generation to be able to cover almost 92% of all new connections made. Wind power mini-grid requires at least an investment of US$1.6 million in total. From this amount, US$0.25 million goes to the LV distribution network, US$0.21 million is invested towards new connections, US$0.92 million goes into capacity generation, and US$0.25 million is invested towards recurring costs. Hydropower mini-grid needs at least US$0.2 million in investment, where about US$0.14 million is invested towards capacity generation, new connections, and LV distribution network. US$0.03 million covers recurring costs.

From the intermediate year to the end year (2030), grid technology needs a total investment of around US$237.5 million. US$103.58 million is a direct investment into the MV transmission network. The LV distribution network required investment is around US$10.89 million and the investment into 38 MW capacity generation is about US$35.6 million. Recurring costs total US$86.39 million while new grid connections need an investment totaling US$71.19 million. During this period, grid extension accounts for most connections which require a huge investment into them. The total stand-alone PV systems total investment amounts to US$7.31 million of which about 90% goes towards additional capacity generation and 10% covers recurring costs. Investment towards wind power mini-grids totals $0.68 million where US$0.07 million is an investment into new connections, transmission and distribution networks.

US$0.61 million goes towards new capacity generation and recurring costs.

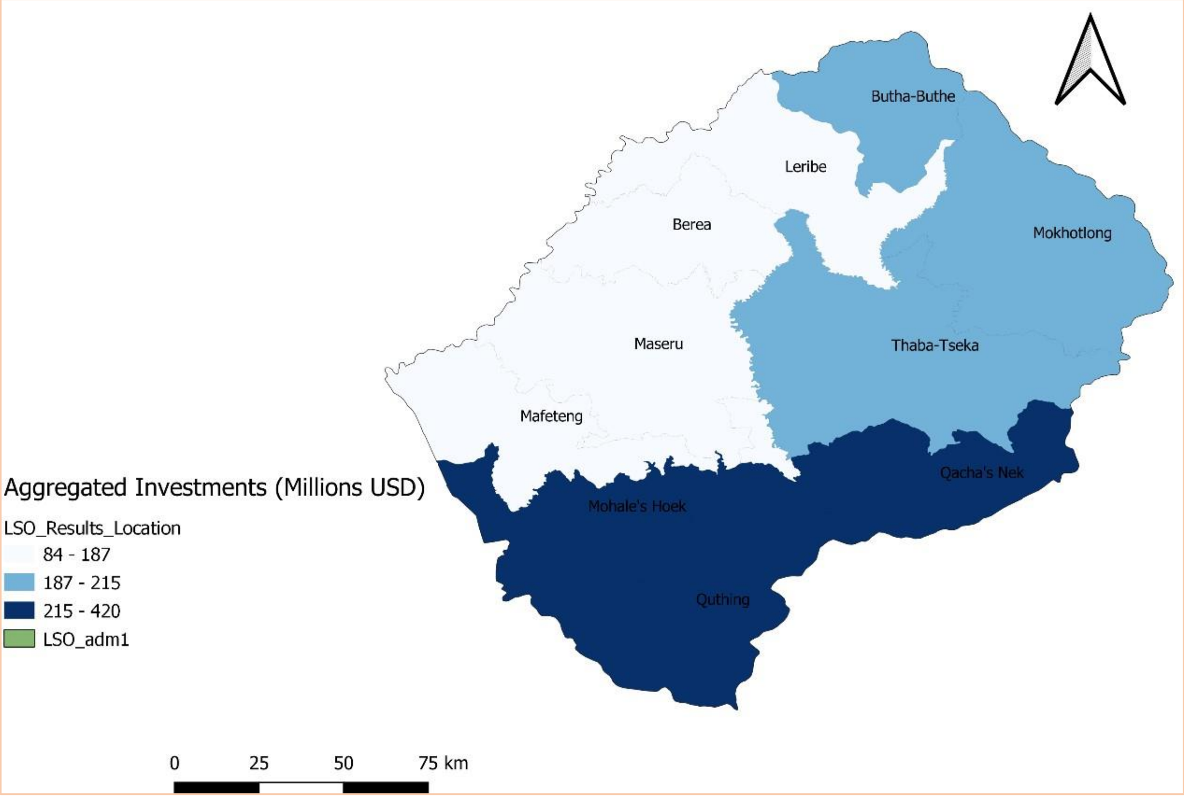


Figure 22: Aggregated investments by 2030 for reference scenario

From a geospatial point of view, Figure 22 illustrates how investments are spread throughout the country. Urban areas such as Maseru, Leribe, Berea and Mafeteng are located throughout the lowlands of Lesotho, and they need the least overall aggregated investment in the range between US$84 and US$187 million in total to achieve 100% electrification. Butha-Buthe, Mokhotlong and Thaba-Tseka districts need aggregated investments between US$187 and US$215 million in total to be fully electrified according to this scenario. Mohale’s Hoek, Quthing, and Qacha’s Nek are the three districts that need the most investment for them to be fully electrified. They need a total investment of around US$215 to US$420 million. Both Figure 19 and Figure 21 explain why Mohale’s Hoek, Quthing, and Qacha’s Nek districts need the most investments. Figure 19 shows that the model prefers electrifying these places mostly through grid expansion which is roughly expensive compared to off-grid options while Figure 21 illustrates that these three districts need the most additional capacity generation by 2030 compared to the other districts across the country.

4.6 Sensitivity Analysis Results

The sensitivity analysis carried out in this study considers high demand, low demand, low solar PV costs, and population growth rate as the most crucial parameters in determining the least-cost electrification technology split and investment costs required for Lesotho to achieve a 100% electrification rate by 2030. The analysis results are shown from Figure 22 to Figure 25. All these parameters are relative to values and the levers used so far in the study when building the reference scenario.

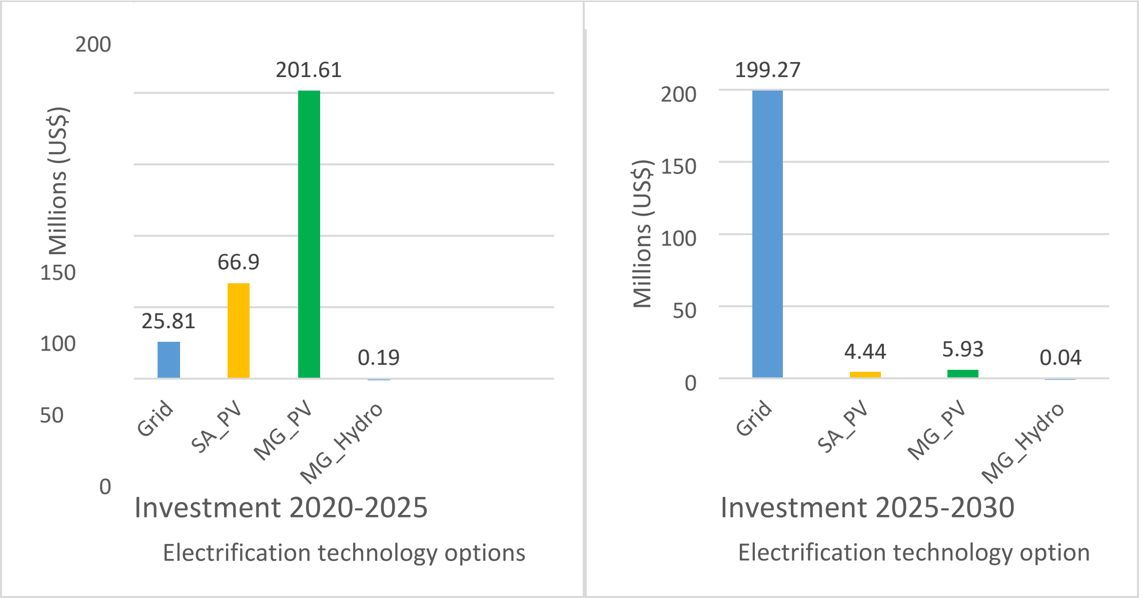


Figure 23: Scenario 1 - Technology mix and estimated investments

Scenario 1 considers a higher electricity demand target with urban areas at tier 5 while rural areas are at tier 3 of electricity access. Figure 22 shows that the least-cost electrification mix is composed of grid connections, stand-alone solar PV, solar PV mini-grids and hydropower minigrids. The total investments required in this scenario are estimated around US$513.19 million from 2020 to 2030. In the first five years of the analysis, the electrification investment totalled US$294.51 million. Solar PV mini-grids require around 68.5% of this investment while 22.7% is towards the stand-alone solar PV system. Grid extension and hydropower mini-grids require around 8.8% and 0.06% respectively, with the latter requiring the least investment among these electrification options. For the last five years of the analysis, the investments total US$209.68 million of which 95% is towards grid extension with the remaining 5% shared among the other three technology options.

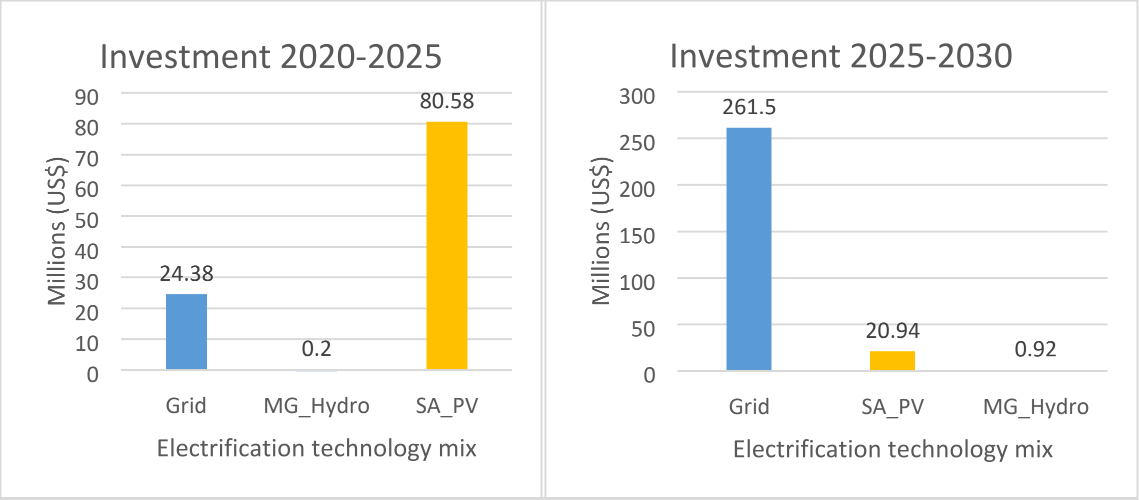


Figure 24: Scenario 2 - Technology mix and estimated investments

Scenario 2 considers low electricity demand where urban areas have a tier 4 level for access to electricity while rural areas have a tier 1 level. Figure 23 illustrates the electrification analysis of this scenario where the least-cost electrification technology mix includes grid, stand-alone solar PV systems and hydropower mini-grids. The analysis yields a total investment estimated around US$388.52 million which is required to achieve a 100% electrification rate by 2030. From the start year to the intermediate year, the required investment is around US$105.16 million where 76.8% of this investment is towards solar PV systems and 23% is towards grid extension. Hydropower mini-grid systems only account for 0.2% of the investments. The required investment for the period from the intermediate year to the end year of the analysis is around US$283.36 million. About 92.3% of this investment is towards grid extension, 7.4% is towards stand-alone solar PV systems and 0.3% is towards hydropower mini-grid systems.

Scenario 3 is based on the reduction of the solar PV cost factor by 50%. The least-cost electrification technology mix includes grid extension, stand-alone solar PV systems, and solar

PV mini-grid systems. As illustrated in Figure 24, in the first term of the analysis, only grid and stand-alone solar PV technology are applicable in this scenario while in the second term, all three electrification technology options are applicable. The total investment required in this scenario is estimated at around US$300.02 million. The first term requires around US$75.53 million where 69% of this investment is towards electrification through stand-alone solar PV systems and the remaining 31% is towards electrification through grid extension. For the second term, the estimated investments total US$224.49 million of which 96% is towards electrification through solar PV mini-grids and the remaining 4% is for both grid extension and stand-alone solar PV systems.

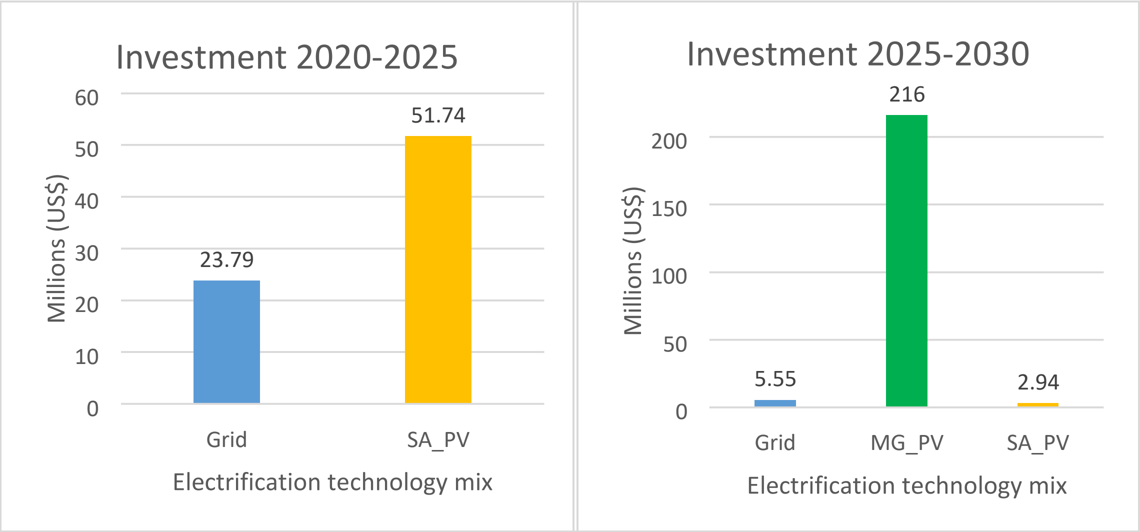


Figure 25: Scenario 3 - Technology mix and estimated investments

The fourth and last scenario assessed what happens when the population growth rate is increased by 2.5% in contrast to the 1.4% growth rate in the reference scenario. From Figure 25, it is observed that three electrification technology options, grid, stand-alone solar PV systems and hydropower mini-grids represent the least-cost options for this scenario. The total electrification investment required by this scenario is estimated at around US$412.75 million. The first term of the scenario requires an investment of around US$133.08 million where 79% is towards electrification through stand-alone solar PV systems, 20.6% towards grid extension and the rest of the investment is towards the hydropower mini-grid. The second term requires a total investment of US$279.67 million of which 96.6% is towards electrification through grid extension and the rest is towards stand-alone solar PV and hydropower mini-grid.

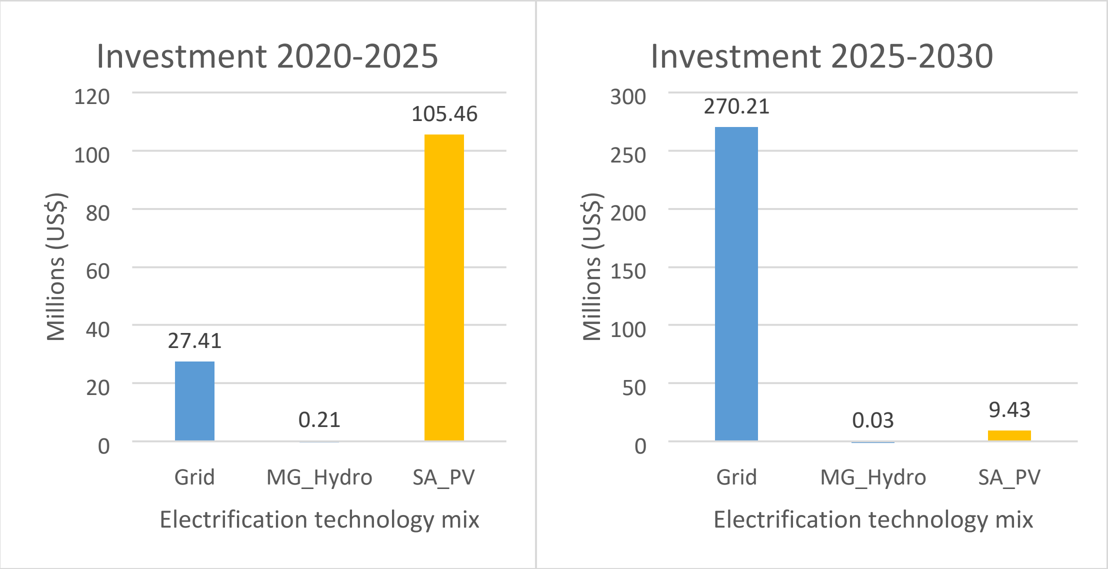


Figure 26: Scenario 4 - Technology mix and estimated investments

The sensitivity analysis from different scenarios and the generated main findings are compared and contrasted with the reference scenario results in Table 6. Scenario 1 (high electricity demand scenario) and Scenario 4 (increased population growth rate) require higher electrification investments than the reference scenario (BAU) whereas scenario 2 (low electricity demand) and scenario 3 (reduced solar PV cost factor) require fewer investments compared to the reference scenario. When looking at the electrification technology options, all scenarios, including the reference scenario, have the grid and stand-alone solar PV systems. In addition to these two, the reference scenario uses hydropower and wind mini-grid systems while the high demand scenario opts for solar PV mini-grid instead of wind mini-grid compared to the reference scenario. In scenario 3 where the solar PV cost factor is reduced by 50%, the solar PV technologies, both stand-alone and mini-grid systems are largely opted for. Regarding additional new capacity, only scenario 3 required few capacities than the reference scenario.

Table 6: Comparison of reference scenario with other scenarios

Scenarios	**Total required investments ($ millions)**	**Technology mix (% shares)**	**Additional capacity required (MW)**

Reference (BAU) Urban- tier 4 Rural- tier 2 PV cost factor (1) Pop growth rate (1.4%)	401	• Grid (53.14) • SA PV (46.12) • MG wind (0.64) • MG hydro (0.09)	90
1 - High demand (Urban- tier 5	513.19	• Grid (74.29) • SA PV (12.01)	155
Rural- tier 3)		• MG PV (13.11) • MG hydro (0.59)	
2 - Low demand (Urban- tier 4 Rural- tier 1)	388.52	• • Grid (53.27) • SA PV (46.64) MG hydro (0.09)	81
3 - Solar PV cost factor (-50%)	300.02	• • Grid (29.83) • SA PV (46.74) MG PV (23.43)	215
4 - Higher population growth rate (2.5%)	412	• • Grid (53.26) • SA PV (46.65) MG hydro (0.09)	94

4.7 Results Discussion

GIS-based electrification planning using OnSSET/GEP can play a crucial role in attempting to answer the challenges that traditional planning methodology faces, such as not being costeffective and taking a lot of time when planning to electrify areas of interest. This kind of innovative electrification planning can visually map out information that, in turn, easily informs policymakers and governments on how to tackle the lack of access to electricity effectively. Like most countries across the globe that still have the vast majority of their population without access to electricity, Lesotho wants to do whatever is possible for it to achieve SDG 7. Provision of clean and affordable energy, specifically focusing on electricity, is not an easy task as it requires a lot of research, planning and huge amounts of investments to ensure sustainability, both economically and environmentally.

This study has attempted to answer questions such as what is an optimal least-cost electrification technology mix that Lesotho can use to achieve 100% electrification by 2030. What will be the share of each technology throughout the country? What is the total additional capacity required to achieve SDG7? What is the total investment needed to ensure 100% electrification in Lesotho? Answers to these questions as provided in Sections 4.1 to 4.6 by the OnSSET/GEP simulation results which offer some meaningful insights into decision-making regarding electrification planning for Lesotho.

For instance, it can be observed that the simulation results suggest that the least-cost electrification can be achieved through grid extension, stand-alone solar PV systems, wind power mini-grid and hydropower mini-grid electrification technologies. The overall LCOE depicted in Figure 18 indicates that electrification through the grid is more affordable in areas around the already existing grid network (a buffer of 1.5 km) while for areas beyond the buffer, off-grid technologies are more ideal. However, when considering affordability, there is a need for subsidies for areas electrified through off-grid technologies as the LCOE is much higher.

The total investment required for Lesotho to achieve universal access from 2020 to 2030 is estimated at around US$401 as per the BAU or reference scenario which this study elaborates in detail. This value is within a reasonable margin with the value of US$470 million estimated for Lesotho by Mentis et al. [9]. Concerning additional new generation capacity, the simulation results indicate that a total of 90 MW is required to achieve universal access. Considering that by 2020 the peak demand was around 180.57 MW, an additional 90 MW makes the total capacity by 2030 to be around 270.57 MW. This resonates with the BAU demand forecast of about 255 MW by 2030 established by Senatla et al. [18] and the 275 MW demand forecasted by Mpholo et al. [23]. Furthermore, the sensitivity analysis indicates that a higher electricity demand requires more investments and that grid and mini-grid technologies become more affordable for such conditions. However, for low electricity demand, stand-alone solar PV technology becomes a more prominent option for electrification because of being cheap. This is also true for a scenario where the solar PV cost factor is reduced by 50%. When the population growth rate is increased by 2.5%, the required investments become a little more than in the reference scenario.

Lesotho through its latest energy policy (2015-2025) clearly outlines its intentions on supporting the initiatives that promote energy access within the scope of reliability and affordability as a way to both socially and economically develop its people [74]. Since electricity is the most crucial energy carrier, it is believed that the anticipated socio-economic development can only be more realistic if access to electricity is improved sustainably with a minimal negative impact on the environment. One of the objectives of this study is to contribute to the development of a visual, interactive and effective rural electrification master plan as part of a wider national integrated resource planning which aligns perfectly with the national energy policy statement two (2) regarding information management and outreach. The statement stipulates that the government wants to improve access to energy resources data and information and also to increase the knowledge among its citizens of all the available energy resources, electrification technologies and their socio-economic parameters. From this study, it can be known which electrification technology is economically and environmentally suitable for which part of the country or settlements in general and also how much investment needs to be raised to electrify such places.

Lesotho has an electrification master plan that shows how the grid network can be developed from 2017 to 2036. This plan takes into consideration areas that are economically feasible to electrify through grid extension [63]. At the same time, it is meant to enable off-grid power roll-out planning in a systematic and equitable manner. This shows that the government of Lesotho considers electrifying the country through both grid and off-grid connections. The results of this study indicate that universal access can be achieved through a mix of grid and off-grid technologies and, to some degree, grid intensification and coverage according to this analysis matches with the planned grid extension according to the electrification master plan. However, there are certain places such as the areas in Mafeteng and Maseru that the OnSSET/GEP model chose to electrify with off-grid technology such as the stand-alone PV systems even though the national electrification master plan intends to electrify them through the grid. One aspect of why the model chose stand-alone PV over the grid is the low demand for such clusters, as this data was not available when developing the electrification master plan. Instead, the enumerator area data from the 2016 census was used as the base for planning. On the other hand, the GIS population cluster data used when modelling had the demand estimates per cluster. Thus, the model found stand-alone PV systems more economically feasible for electrifying such areas.

GIS-based electrification planning has some limitations and/or challenges. One major challenge, especially in the least developed countries, is the availability and reliability of GIS datasets. For Lesotho, most of the basic geospatial data is not available at a granular level. For example, geospatial datasets involving the LEC grid network are not regularly updated and have some gaps within them. The existing transmission and distribution network shapefiles found at ENERGYDATA.INFO [75] were last updated in 2017, yet there has been a significant addition to the network post that period. The geospatial datasets representing planned HV and MV networks are not publicly available. Socio-economic geospatial datasets that play a crucial role in electrification planning are still also not publicly available. For instance, Lesotho lacks geospatial datasets that describe energy demand, income level, energy expenditure, productive usage of energy by sectors and up-to-date poverty maps, among others. Some of the publicly available geospatial datasets such as the Lesotho population clusters lacked some proper metadata describing the demographic characteristics of such clusters. Modelling with this kind of data leads to assumptions that increase the uncertainty of GIS-based electrification analysis. Furthermore, geospatial data of an open-access nature requires researchers to run quality assessments before using it because sometimes the dataset origins are unknown or the data itself is doubtable. These processes require lots of time and resources.

Similar previous studies using OnSSET [9, 11, 72] looked at the challenges that the GIS-based electrification modelling tools have. One is the integration of the energy system models with GIS as both energy models and geospatial analysis processes are complex in combining model parameters to mimic the model onto the real world as best as possible without too much simplification. Some of these tools are described as proprietary because they fail to provide an electrification extension plan for the entire country. They lack grid expansion algorithms and they do not take care of dynamic change in the bulk supply of grid electricity. OnSSET, which is used in this study, considers myopic optimization and thus does not use perfect foresight. It also uses electricity demand layers imported from external calculations. This only provided informed estimates. However, this tool is quite simple as its interface is user-friendly. One way to mitigate some of these problems, especially those concerning geospatial data availability and validation for developing countries such as Lesotho is the establishment of open-access databases by international development bodies. This can be achieved through supporting local institutions in collecting and providing such data. The World Bank group is making an effort in that regard through the ENERGYDATA.INFO database [64]. Another way would be to create a global partnership aiming to enhance and promote collaboration between various actors who develop energy modelling tools, those who collect and create geospatial data and those who manage and use such data.

5. Conclusions and Recommendations

OnSSET is an energy planning model integrated with geospatial analysis to improve GIS-based electrification planning and has been used in this study to carry out GIS-based electrification planning for Lesotho. OnSSET is used over similar models, mainly because of its robustness and advancements in geospatial analysis and improved data availability. It assesses what can be done to ensure universal access to clean and affordable electricity in Lesotho by 2030 through running the electrification analysis from the year 2020 when the electrification rate was 47.3% nationwide to 2030 in support of SDG7. It also provides answers on how the status quo of the Lesotho power sector can be able to provide a route for universal electricity access by 2030 and beyond and what technology types should be used for electrification.

The LCOE plays in a critical role in the electrification analysis as the technology selection and investment options are based on it. For the reference scenario, the electrification analysis suggests that Lesotho can be electrified through both on and off-grid technologies. The existing grid network will be extended to allow intensification within a buffer of 1.5 km of the grid and the LCOE from the grid is found to be around 0.087 US$/kWh by 2030. Off-grid technologies that make up the electrification mix include stand-alone PV systems, wind power mini-grids and hydropower mini-grids. Off-grid technologies have their LCOE in a range from 0.229 to 0.8 US$/kWh, with stand-alone systems LCOE around 0.229 to 0.371 US$/kWh and mini-grid system's LCOE being from 0.513 to 0.8 US$/kWh. It is observed that changes in electricity demand levels, population growth rate, and electrification technology costs also have an impact on investment estimates and choice of electrification technology. The LCOE value for grid technology resonates with the current cost (0.086 US$/kWh) of electricity in Lesotho, which is subsidized by the GoL. On the other hand, this study indicates that off-grid systems have high LCOE and it is recommended that they too be subsidized to encourage acceptability and usability by the people in Lesotho. Diesel was completely omitted from the analysis because of its negative impacts on the environment and because Lesotho has adequate renewable potential without the use of fossil fuels to meet its current and near-future electricity demand. The selection of an optimal electrification technology mix is based on the socio-economic, technological, geospatial, environmental and regulatory aspects of Lesotho.

The total investment required to attain universal access by 2030 is $401.54 million. Electrification through grid connections requires 65.81% of the total investment with off-grid technologies taking up the rest of the investment. Results show that stand-alone PV systems are the least-cost technology for off-grid connections and that it requires around 95% of the total investment towards off-grid electrification technologies. This is because of the low household demands in the majority of settlements in rural areas of Lesotho where the majority of the population resides. In the settlements where the demand increases, wind and hydropower mini-grids are used for connections. In the settlements with higher demand, mainly the settlements in the lowlands or with higher population density, the grid is used for connections. The investment is mainly towards the generation of new, additional capacity, infrastructure and connections. It is also observed that a higher demand requires more electrification investments while a lower demand requires fewer investments for electrification in an attempt to achieve universal access.

With a wide scope of electrification planning analysis, this study can play a crucial part in policy making. The open-source nature of this tool means that data can be improved and updated and more suitable methods can be incorporated. With OnSSET/GEP, effective planning on electrification strategies to be deployed in an attempt to achieve universal access to clean and modern electricity can be achieved. In the case of Lesotho, the results from this study already pave the way for achieving some of its energy policy goals to increase a share of cleaner energy sources in its energy mix and the reduction of non-sustainable forms of energy. Furthermore, this study contributes to the development of a visual, interactive and effective rural electrification master plan as part of a wider national integrated resource planning. It is through this plan that participation of the local private sector and cooperative bodies can be improved within the energy sector through engaging in business practices that deal with electricity supply and generation. This study fast-tracks progress towards the improvement of the livelihoods for Basotho people as implementation and improvement in electricity access across the country improves economic growth and creates job opportunities. This may alleviate poverty and contribute towards ensuring the security of the electricity supply to meet the country’s electricity requirements.

The major challenge of this electrification analysis is data availability and quality. This can be improved by ensuring the availability of datasets with up-to-date information and being of high quality from sub-national to global levels to avoid some of the assumptions that the model makes in the absence of some datasets. The model itself can, however, still be improved further to ensure a robust analysis. This can be done through taking into consideration the suggestions made by [71] and the model can assume initial electrification not to take place only through the grid as this brings some discrepancies in the electrification rollout plan from the analysis.

One area that could further be elaborated on this study is the social and environmental impacts of the proposed electrification technologies on different communities they are to be installed in. Moreover future research studies on geospatial electrification planning in Lesotho can focus on the calibration of energy planning levers, technology specifications and future investment outlooks regarding sustainable energy.

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Appendix

Appendix A: Modelling parameters for the reference scenario

Variable	Value
Start year	2020
End year	2030
End-year electrification rate target	1
Intermediate target year	2025
Intermediate electrification rate target	0.75

PV cost adjustment factor	1
Urban target tier	4
Rural target tier	2
Prioritization	6
Auto intensification distance km	1.5
discount rate	0.08
pop threshold	0
pop_start_year	2142249
pop_end_year	2325164
urban_ratio_start_year	0.29
urban_ratio_end_year	0.319
num_people_per_hh_urban	4.5
num_people_per_hh_rural	6.1
elec_ratio_start_year	0.473
urban_elec_ratio	0.88
rural_elec_ratio	0.11
grid_generation_cost $	0.087
grid_power_plants_capital_cost $	1363
grid_losses	0.167
base_to_peak	0.8
existing_grid_cost_ratio	0.1
diesel_price $	1.25
sa_diesel_capital_cost $	938
mg_diesel_capital_cost $	721
mg_pv_capital_cost $	2950
mg_wind_capital_cost $	3750
mg_hydro_capital_cost $	3000
sa_pv_capital_cost_1 $	9620
sa_pv_capital_cost_2 $	8780

sa_pv_capital_cost_3 $	6380
sa_pv_capital_cost_4 $	4470
sa_pv_capital_cost_5 $	6950
mv_line_cost $	7000
lv_line_cost $	4250
mv_line_capacity $	33
lv_line_capacity $	0.24
lv_line_max_length km	0.5
hv_line_cost $	53000
mv_line_max_length km	50
hv_lv_transformer_cost $	25000
mv_increase_rate	0.1
max_grid_extension_dist	50
annual_new_grid_connections_limit_intermediate	7756
annual_new_grid_connections_limit_end	1E+09
grid_capacity_limit_end	1E+09
grid_capacity_limit_intermediate	50