



National University of Lesotho



Optimized network planning of electrification projects in remote areas of Lesotho

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Abstract

The United Nations has, in 2015, adopted an urgent call for action by all countries for the implementation of Sustainable Development Goals (SDGs) which among them is access to affordable, reliable, and sustainable energy for all (SDG7). The call led to an increase of 120 million people gaining access to electricity each year but declined in 2020 and 2021 due to the coronavirus pandemic. So far, tools have been developed and several approaches have been applied to solve rural electrification problem but they often neglect the important spatial information such as population distribution which is one critical drawback. These data are important for the design of electrical networks hence when neglected lead to systematical capital investment miscalculation. The proposed strategy in this study utilizes a Geographic Information System (GIS) and terrain analysis to create an optimum electric network topology of the proposed case study involving the rural areas of Butha Buthe district in the mountains of the Kingdom of Lesotho. Furthermore, the geospatial-based procedure for rural electrification planning will be able to select and design an effective energy system for the defined geographical region to identify the least-cost solution to the existing national grid of non-electrified communities. The simulation tool to be used in this study, herein called GIS for Electrification (GISEle), focuses on data analysis and exhausts all means leading to the identification of the optimal techno-economic solution where energy lacks. The collected spatial data is exploited to identify populated areas and subdivide them into clusters thereafter designing the electrical network connecting those clusters with minimized costs. The performance of the procedure has been tested in 10 villages in the rural areas of Butha-Buthe, Lesotho. The analysis shows that the geospatial tools are very important but work best on the application as per the need of the specific demand of the client. In this case, the model demonstrated huge achievement and design time saving as the electrical designers do not have to re-design the network when designs are now transferred from paper to the ground. GISEle looks at all aspects from terrain to road access making it easier for operation and maintenance purposes. The total GISEle costs for Makhunoana 1 community council are M1, 117, 517.12 which is lower than the cost price of M2, 475, 000 from the Electrification Master Plan (EMP). The overall costs for Ts'a-Le-Moleka community council using GISEle tool are M1, 385, 229.12 and they are lower as compared to the overall cost of M1, 815, 000 from the EMP. Furthermore, the overall GISEle electrification cost for Makhunoana 2 are M1, 107, 741.12 with a slide difference from M1, 095, 000 from EMP study. Lastly, Ntelle GISEle electrification costs are M2, 004, 440.96 and are also lower compared to the M2, 070, 000 from EMP. This figures mean that GISEle is more preferable than EMP and more viable as the electrification planning demonstrated detailed design not estimates as the case for EMP.

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Chapter 1: Introduction

1.1 Background

Access to electricity is one of the significant drivers of the country's socio-economic development [1],[2]. About 84% of the world population, out of over one billion people lacking access to electricity, lives in remote areas [3]. The worse trends are found in sub-Saharan Africa and Southeast Asia [1]. Electricity contributes to the improved health care system, education, environmental sustainability, and agricultural development hence the UN Sustainable Development Goal 7 (SDG7) aims to increase affordability and access to clean energy for all [4]. However, increasing access in sub-Saharan Africa proved to be difficult and expensive hence policymakers and planners need to develop tools that will enhance electrification efforts to meet economic demand [5]. Rural electrification is generally considered to be expensive due to poverty, low demand, and sparse population density among other factors [6]. Like most of the sub-Saharan African countries, Lesotho's main focus through the Ministry of Energy is to intensify electricity access to urban, peri-urban and rural areas within a reasonable distance from the existing electricity grid network [7].

The universal access to electricity target set by the 2030 Agenda is significant as it involves reaching a population often living in sparsely populated areas with limited income [8]. The other difficult part is the selection of the optimal electrification approach and an example will be grid vs. off-grid, fossil fuel vs. renewable, and public vs. private investment [9]. Nevertheless, dealing with this kind of issues involve the deployment of huge technological systems that requires analysis of the social, technical, economic, and political characteristics [9]. This in turn requires reliable access to data and information such as the density of population settlement, electricity demand, resource availability, and distance from infrastructure (grid and roads network) [9]. With the increasing new data and analytical tools especially in the field of geospatial analysis, the difficulty in accessing the official information situation is gradually being overcome [10].

The electrification plans based on geographical information systems (GIS) depend on the availability of updated records of the existing infrastructure. The important input parameter to the Geographic Information System for Electrification (GISEle) which this study will be focusing on is the distribution of the grid network. Optimization to minimize the cost of electricity is required for each stage while also maintaining an acceptable level of reliability [11]. The unelectrified settlements are more economical to connect to the existing national grid if transformers of medium voltage (MV) lines are close. Despite the proximity, the low-quality datasets of the grid network may have impacted the results of electrification models. Similarly, areas that are situated far away from the network might opt for an alternative source of supply (off-grid technology) [12].

1.2 Problem Statement

This study attempts to provide the solution to incurred problems of network planning in the rural areas of Lesotho. Currently, the Lesotho Electricity Company (LEC) enjoys the monopoly of being the only power utility company in Lesotho and its mandate among others from the Department of Energy (DoE) through the Rural Electrification Unit (REU) is to plan and implement the rural electrification projects. Since the rural electrification projects are influenced by politics or the sitting government, this leaves LEC with a mammoth task in planning electricity network extensions within a short period, even on projects that are out of the grid access or those that can be electrified with mini-grids or standalone systems. This problem leads to improper design of the grid network, either over- or under-design, as LEC currently has no tools available to assist the department of planning and projects to effectively and efficiently deal with this task. Over-design or wrong choice of electrification option leads to the government overspending a lot of money on the project that does not have any return on investment with few connected customers. Moreover, LEC loses more in operation and maintenance costs that could have been avoided in the planning stages of the network by making the right choice of electrification option. Likewise, under-design also hits hard on the LEC pocket as it automatically inherits the poor design after the completion of the project, hence spending more money for system improvements or rehabilitation that could have been utilized elsewhere.

1.3 Research Question and Objectives

Generally, access to electricity in Lesotho especially the grid extensions in the rural areas have proven to be more expensive with limited connections. The purpose of this study is to:

- To develop a methodology to approach rural grid electrification at national level in a comprehensively planned manner focusing on grid extension only
- To introduce a tool based on GIS software (GISEle) that can come up with the optimal infrastructure and cost indicators for electrification
- To apply the GISEle to Lesotho and demonstrate the results in interactive and easily understandable maps and tables

To meet these objectives, the research seeks to answer the following question:

- ❖ How can LEC improve the current electrification network planning approach and how the GISEle can help optimize the network planning to save costs that are incurred due to over- or under-design?

The following sub-questions will also be addressed:

- ✓ What is the current model that LEC utilizes for network electrification planning?
- ✓ What are the challenges and shortcomings of the current model?
- ✓ How can the model or approach to rural electrification planning be improved?
- ✓ How can the improved model benefit both LEC and the government in terms of costs of universal electricity access in the country?

- ✓ What is the most cost-effective way to electrify the population in the last mile, what technologies and costs would that imply?

1.4 Justification

Electricity is one of the significant drivers of the socio-economic development of a country that contributes to a better health care system, education, and environmental sustainability [1]. A lot of research has been conducted in the past for the network planning of rural electrification but such studies according to the authors' knowledge have never been done in Lesotho. Similar studies have been undertaken for the cases of Nigeria, Tanzania and Malawi to name a few in sub-Saharan Africa [18]. The strategy to be developed in this study will lower electrification costs to meet the economic demand of Lesotho. The study focuses on the areas of significant potential in terms of benefiting the government, LEC, and the rural community as service connections will be increased with the same investment and will contribute to meeting the SDG7 targets in 2030. The results from this study should help the policymakers in deciding whether the connections will be on-grid or off-grid depending on the general costs of the implementation of the project. The time consumed and the gap between planning and project implementation will be reduced by automation of the routing process, allowing the short time of multiple routing solutions [13].

1.5 The organization of the study

The study is made up of five chapters. Chapter 1 gives the background and objective of the study. Chapter 2 starts with the literature review which comprises the foundation on which the methodology has been built and consists of an exposition of the mathematical instrument applied to accomplish the work together with an analysis of proprietary software. Chapter 3 is dedicated to the detailed description of the study methodology developed using the open-source GISEle software. Chapter 4 gives the simulation and optimization results and goes through the discussion of the study together with accomplished objectives. Eventually, Chapter 5 presents the conclusions and recommendations for further direction to follow for improvement of the project in the future.

Chapter 2: Literature – Algorithms and Models Review

2.1 GIS Overview

Models and algorithms are effective electrification planning tools which rely on or are rather based on GIS tools to perform geospatial analysis. It is therefore important to have a better understanding of both algorithms and models. Nowadays GIS technology incorporates geographical information into one analytical model in which data is projected from geo-referenced information. GIS sums up different subject areas hence it is difficult to define the term, but the accepted definition is provided in the National Centre of Geographic Information and Analysis (NCGIA) [14]:

GIS is the system which comprises hardware, software and procedures that manage, manipulate, analyse, model, represent and display georeferenced data to solve complex problems in so far as planning and management of resources are concerned.

GIS normally works with two types of data that are different: raster type or vector type as illustrated in Figure 1. Vector data presents discrete data which are the real world features that contain attributes, text or numerical information within a GIS environment to describe them. Furthermore, it represents features by a form of geometry (point, polygons, polylines) made up of one or more interconnected vertices [15]. The vertex position is located using the X and Y-axis in the space. These data can represent for example trees, roads, and buildings whereas Raster data are composed of matrices of pixels called cells.

Raster data represent data that changes continuously in space as each pixel or cell contains values that represent the nature of the covered area by the same cell. For example, the density of cover for grasslands and variation of colour is better represented by raster data whereas if vector data is used, such information would be lost in the process of altering the feature into a single polygon [16]. The GIS data collection composes a layer that can be composed of raster or vector data.

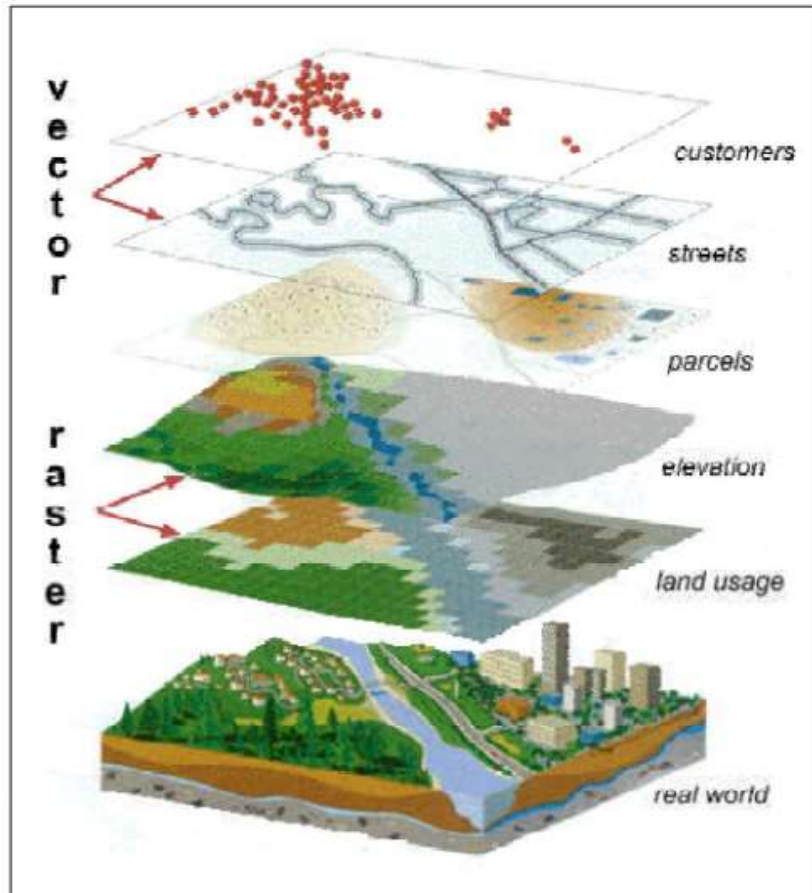


Figure 1: GIS map composition of raster and vector data (Source: [16])

2.2 Graph Theory

The key strength of the proposed study is the ability to track the topology of the electric network with the ability to make estimates of the capital cost. Graphs are the simplest way of representing network topology such as the electric grid. For a long time, it has been tried to solve real problems through mathematics. The origin of the graph theory comes from a historic notable problem by the name of “The Seven Bridges of Konigsberg” which mathematician Euler solved [15]. Graphs are now widely used in different applications, from biology and computer science. This optimization problem deals with applications of advanced analytical methods assisting in making better decisions in most fields.

Graphs have various types and the term is most of the time used loosely. In this work, graph theory represents an electric network topology. The following definitions best suit the goal of this study:

2.2.1 Graph

$G = (V, E)$ thus graph G is a pair where:

- V is called vertices of G , and
- E is called the edges of G

This study further aims to deal with electrification and grid planning to connect loads. This can be represented by employing electric lines through the use of vertices and edges, with the possible lowest cost. Loop is an edge connecting a vertex to itself which requires an edge made by a single element of subset V [15]. It is not necessary to create a connection from the load since the whole idea is to represent an electric network as a graph. A graph can be divided into two classes which are undirected and directed which sometimes are called a digraph. It has edges in which the direction is associated with them and represented by the position order. This is very important when analyzing the power flow of the network in the power system as information on the direction of power generated or absorbed is very crucial [15].

2.2.2 Path

Let e_1, e_2, \dots, e_{n-1} be a sequence of elements of E (edges of G) for which there is a sequence a_1, a_2, \dots, a_n of discrete elements of V which is the vertices of G such that $e_i = \{a_i, a_{i+1}\}$ and $i = 1, 2, \dots, n - 1$. The sequence of edges e_1, e_2, \dots, e_{n-1} is called a path G [17].

2.2.3 Connected graph

If $G = (V, E)$ is a graph, then there is at least one path connecting u and v for any two distinct vertices u and v of V , then G is a connected graph [15].

2.2.4 Tree

The G is called a tree (T) if it is a connected graph without a cycle. Thus, a tree is a graph where there is exactly one path from u to v if for every pair of vertices $u \neq v$ in G .

2.2.4 Forest

Forest is described as a graph whose all connected components are trees. The forest with only one component is particularly a tree. Figure 2 depicts a typical example of the graph, connected graph, and a tree.

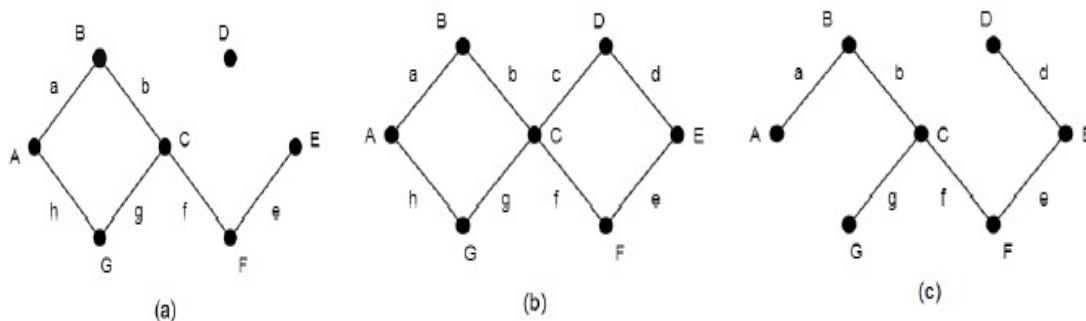


Figure 2: (a) Graph, (b) Connected graph and (c) Tree (Source: [15])

2.2.5 Spanning Tree

"A spanning tree of a graph $G = (V, E)$ is a sub-graph $T = (V, E')$ which is a tree and has the same vertices as G ". From the tree shown in Figure 2, we can derive a spanning tree of the graphs in Figure 2 (a) and (b) by considering each edge e on the graph to be associated with weight $w(e)$ that will represent the connection cost and each different spanning tree will have a total cost that is assigned to it of which it will be the sum of all the weights. From a graph G , all possible spanning tree with the lowest total weights is called the minimum spanning tree and is defined in the following:

2.2.6 Minimum Spanning Tree (MST)

A minimum spanning tree $T = (V, E')$ of a connected graph $G = (V, E)$ is a spanning tree such that:

$$\sum_{e' \in T} \omega(e') \leq \sum_{e \in T'} \omega(e'') \quad (2.1)$$

For every other spanning tree $T' = (V, E'')$

The problem of the minimum spanning tree (MST) revolves around finding the MST of a given graph and establishing it mathematically. Several algorithms have been developed over the years to best find the solution and they are discussed in the next section.

2.3 Heuristic Algorithms

2.3.1 Prim's Algorithm

Prim's is based on a greedy approach and was developed in the 1930s as one of the first solutions to the MST [18]. The procedure of Prim's algorithm is formulated in Figure 3 and depends on the size of the graph in terms of the number of vertices and edges [16]. The following steps articulate this algorithm:

1. To initialize the Tree T , we start by selecting an arbitrary point from the graph $= (V', E') = v_0$ and $E' = \emptyset$
2. If $V' \neq V$, they do the following
 - Find all the possible edges $e(u, v)$ that connects $u \in V$ to $v \notin V'$. Not to mention that $e \subset E$.
 - Select the minimum-weighted edge e and add it to E' and v to V' .
 - Break the loop if there is no possible edge.
3. T will be the minimum MST only in the case of $V' = V$. Otherwise, no MST is found in graph G .

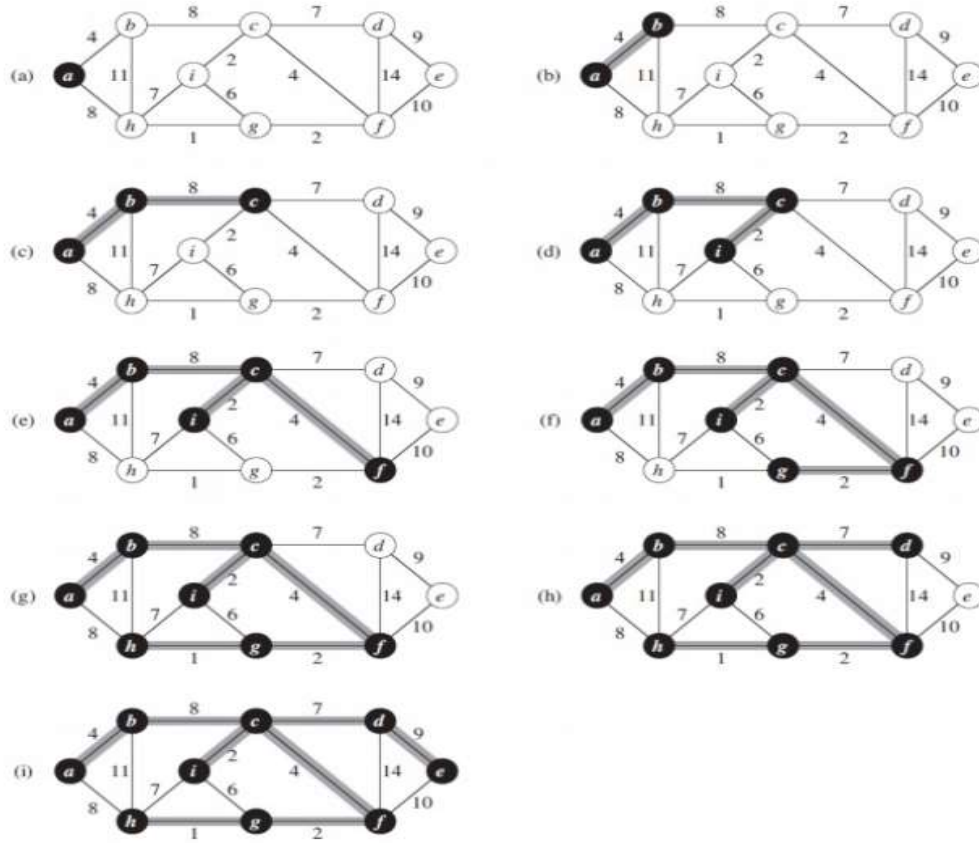


Figure 3: Procedure of Prim's Algorithm to find the MST of the graph (Source: [15])

2.3.2 Kruskal's Algorithm

Kruskal's algorithm is considered a variation of Prim's Algorithm which is another greedy based algorithm [18]. The edges are initially sorted in ascending order based on their respective weight. One edge is removed from the set at the time and when the set is empty all edges will be evaluated completely. The greedy algorithms are categorised as heuristic algorithms because a decision is taken step by step, that is, if an incorrect decision is taken at the beginning of the process the final result will be far from optimal. Kruskal's algorithm process is demonstrated in Figure 4.

The output of the algorithm is MST oriented topology which is more suitable to provide preliminary sub-optimal results due to their low computational time. However, they are not suitable to be applied for the case of electrification networks because their nodes are connected only using straight lines with no intermediate connections possibility.

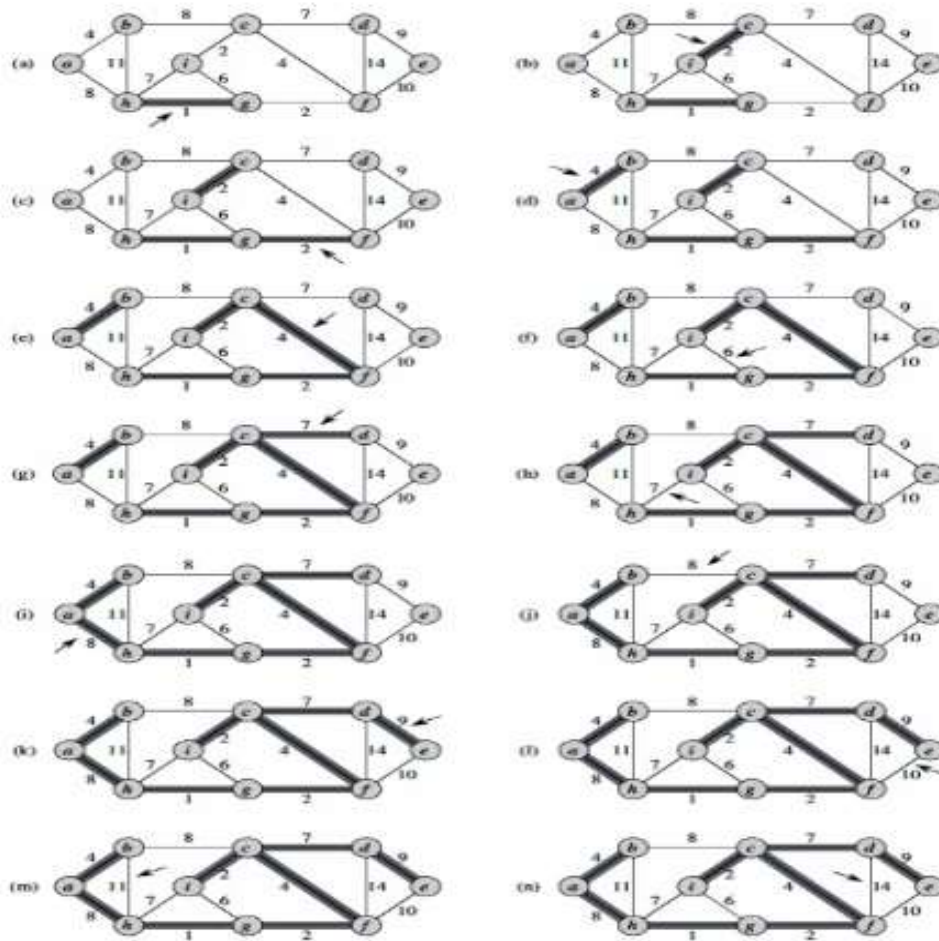


Figure 4: Procedure of Kruskal's Algorithm to find the MST of the graph (Source: [15])

2.3.3 Dijkstra's Algorithm

This algorithm aims to solve the problem of finding the shortest path between two nodes of a graph and it was named after its creator Edsger W. Dijkstra in 1976 [16]. The procedure in finding the shortest path using Dijkstra's algorithms, as an example considering two nodes (source and terminal), can be broken down as follows:

1. T is the minimum path $= (V', E')$ created and contains only the source node.
2. Computation of the distance between the source node and all the other nodes.
3. Distance Matrix is composed where initially the distance $D_{sv} + \infty$ except D_{ss} is equal to zero.
4. For the terminal $t / \in V'$: now Find the minimum-cost edge e connecting u to v where $u \in V'$ and $v \in V'$.
5. e as the new minimum cost is then added to E' and v is added to V' .

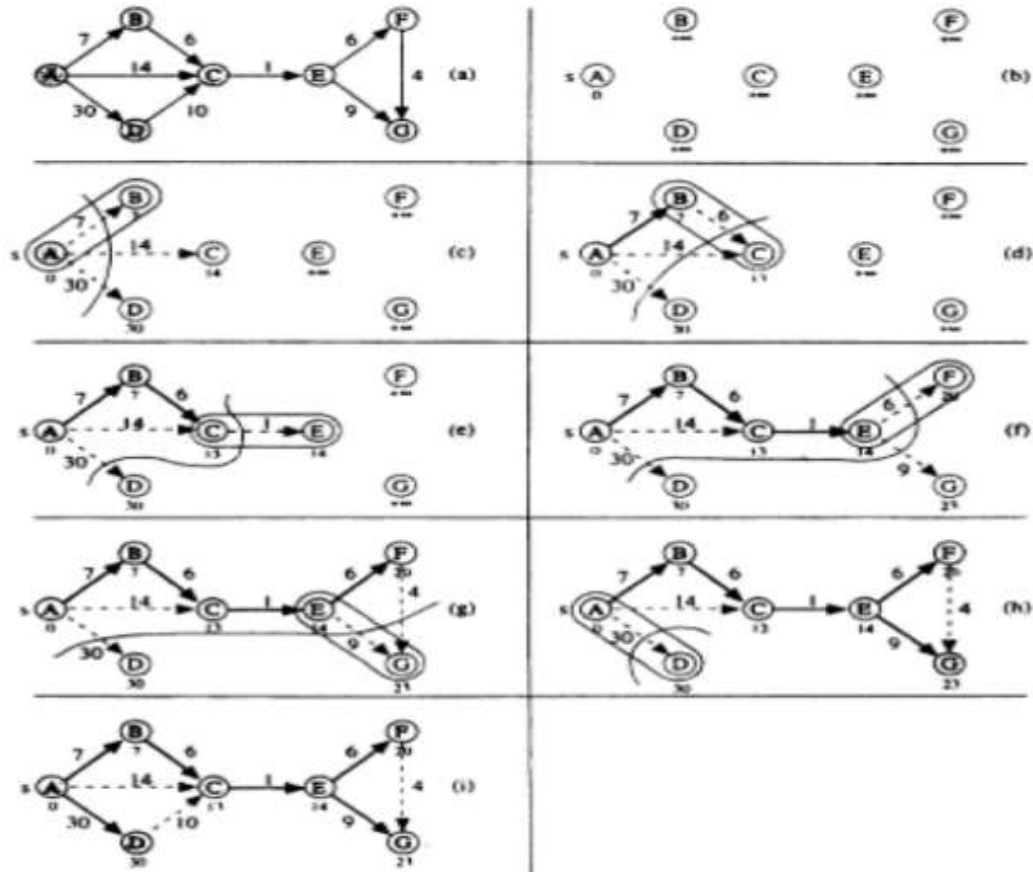


Figure 5: Example of Dijkstra Algorithm (Source: [15])

Dijkstra's algorithm showing the steps to find the shortest path is illustrated in Figure 5. The shortest path between the source node and the target node is the output which does not require all the vertices to be connected. The spanning tree of G is however not composed since the source node is connected to the target node using the minimum path found. The downfall of Dijkstra's algorithms is its ability to connect one source node to just one target node and inability or rather too complex to connect to several terminal nodes that exist in a graph composition of several pool of nodes.

2.4 Numerical Algorithms

The focus of this study is to develop a new GISEle program using Mixed-Integer Linear Programming (MILP) algorithm which now only focuses only on grid connection unlike the previous GISEle program which was comparing the costs of electrification between grid and off-grid systems and used the graph theory algorithm. The main advantage of the numerical algorithm over heuristic approaches is its ability to constrain the optimization to fit the environment of the problem [19]. For power systems, it is possible to limit the optimization of the topology to meet the stability requirements of the power system. The objective function of MILP is to minimize the cost of the network, set constraints that can either be

expressed as linear equalities or inequalities, and a set of decision variables. The optimal path to take can be decided when the decision variables are exploited. For example, if part of the network is a line, the decision variable is 1, otherwise zero is the equality constraint that can be exploited to set the energy balance of the network and set the capacity limit. Shu, J et al developed a GIS Raster-based MILP optimization model for spatial power system planning [20]. To ensure the stability of the power system network, routing is evaluated based on the candidate line routes and the hourly network evaluation for peak power loads. The image shown in Figure 6(a) represents the GIS with the geographical environment information. The resolution r is defined as W / N_R by rasterizing the map into $N_R \times N_C$ square cells where W is the width of the map, N_R are cells in each row and N_C are cells in each column. The assumption is that region covered by each cell has similar altitude and environmental characteristics where Figure 6(b) represents characterized environmental map and Figure 6(c) represents map altitude.

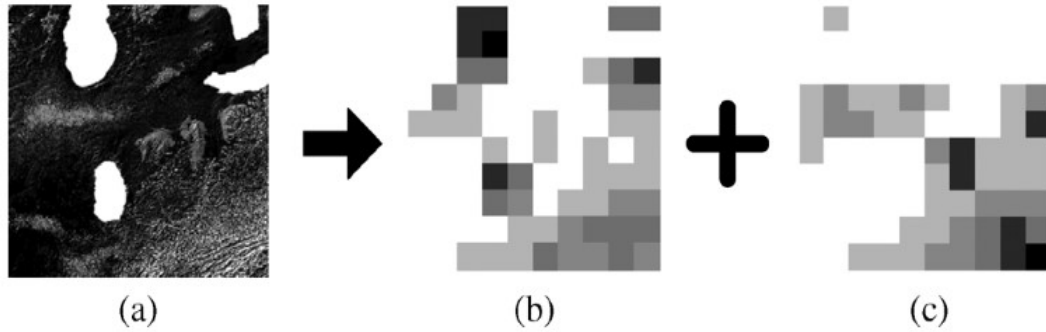
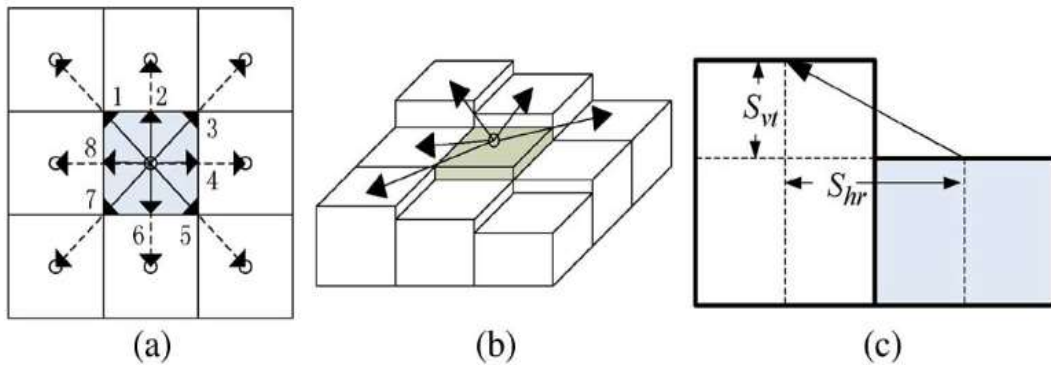


Figure 6: Rasterizing Map (Source: [20])

The terrain cost is related to one spatial aspect which is an elevation in this instance, where only 8 neighbouring nodes from 8 directions follow the grid of points as illustrated in Figures 7. Line 1 to 8 is used to denote the direction where binary variables $x_{i,j,d}$ represents line direction and 1 means the direction d and selected in cell $C_{i,j}$ otherwise zero for $d = 1, 2, 3, \dots, 8$.



Figures 7: Line routes and cells relationship (Source: [20])

The line length is calculated as $\sqrt{S_{hr}^2 + S_{vt}^2}$ from Figures 7 (a) and (b), where S_{hr} is the horizontal differences between two centres of two cells and S_{vt} the vertical differences respectively, where $S_{hr} = \sqrt{2}$ for odd index direction and 1 otherwise.

The results for this model study are shown in Figure 8 considering the terrain cost where it relied on DC power flow for optimization for the technical constraints [20]. The DC power flow results are on the assumption that the voltage profile is flat and the voltage is 1 p.u for all nodes. It is therefore not possible to maintain the voltage within acceptable limits in the context of the distribution system and this is a critical drawback. However, the model is not ideal for checking the optimal capability of the substation to feed the network.

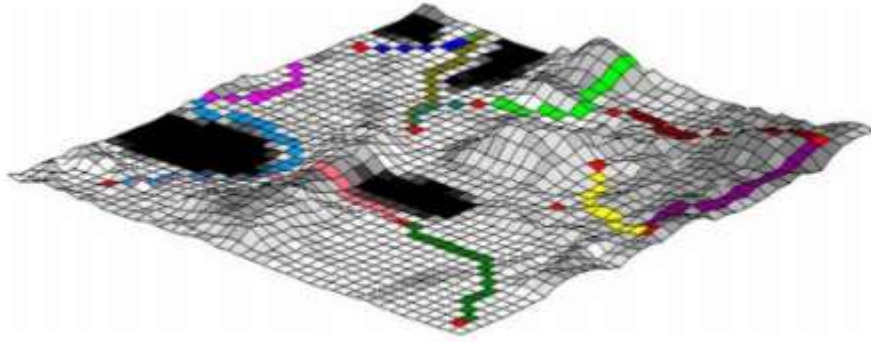


Figure 8: Three-dimensional optimal electrical line routing (Source: [20])

The numerical algorithm developed by Samui et al is based on a direct solution that searches all possible radial paths with the substation root being a path [21]. Graph theory is also utilized for representing the network in this algorithm. From Figure 9, the process starts by creating a graph possible for all the paths and the minimum cost is considered to be the optimal solution with voltage and capacity together with radiality constraints. It uses the theorem of optimality to reduce the number of possible paths on a dynamic programming optimization technique. The theorem states that; the remaining trajectory is optimal for the corresponding problem from any point on an optimal trajectory initiated at that point. For example, if the optimal path to node j involves node i , there is no need to check the optimal path to node i as this way the computational load is reduced heavily.

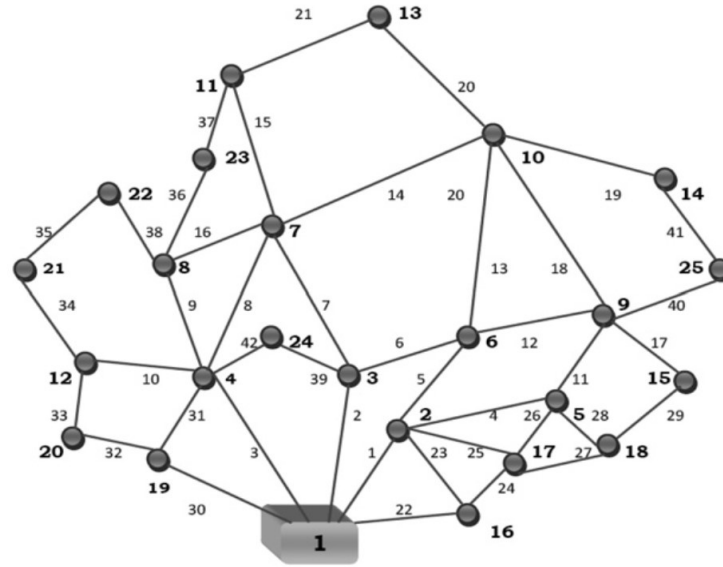


Figure 9: Graph for 24 load nodes possible paths for distribution network (Source: [22])

The cost per kVA including the cost of substation, feeders and energy loss determines the optimal number of substations but the terrain cost is neglected such that is dependent on direct connection without intermediate connection points. Moreover, it is not suitable for large areas applications with thousands of nodes despite minimized computational burden as it will be extremely high computation.

In a numerical algorithm study by Lotero et al, the developed MILP-based approach is in such a way that it minimizes the investment cost, operation and maintenance and reliability cost [23]. The model has several solutions with different reliability percentages used in the distribution system which allows the decision-maker to choose and analyse from a different number of solutions. The model focuses on reliability constraints which is the main advantage as the user can easily customize the system to best suit the reliability level concerning the budget availability. However, the output topology is too simple as the routing does not consider any spatial aspects and assumes the loaded points are an aggregation of demand which in the end simplifies the network.

In Paiva, P.C et al study, the MILP optimization plan for the primary MV grid together with the secondary LV grid is effective [23]. It takes into account the distribution network structure hierarchy as depicted in Figure 10 and most of the research studies have ignored the impact of the LV grid as far as the comparison of the cost of the primary grid the to secondary grid is concerned. Moreover, the planning of both grids is key in achieving a global optimal network as the structure of the secondary grid may affect the primary grid topology.

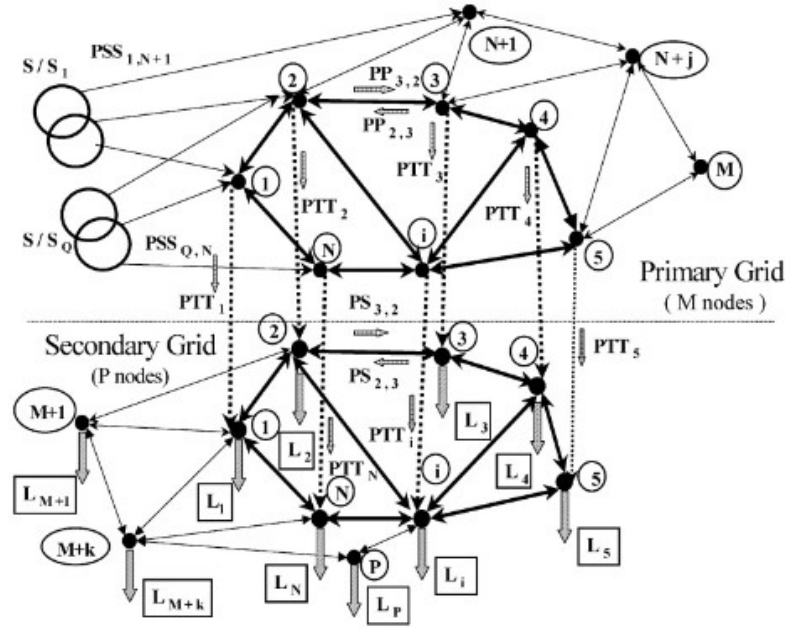


Figure 10: The structure of the distribution system for primary and secondary grid (Source: [24])

In the Ganjavi, M. R algorithm study, MV and LV networks are considered in the two-layer sequential procedure by adaptation of dynamic programming [25]. The optimization of the primary and secondary grid is done separately but simultaneously which is a guarantee of the global optimal solution for an integral distribution system. Furthermore, it allows for the sharing of the line by both primary and secondary grids for minimized costs. The model's drawback is its suitability to be applied to a large-scale network.

2.5 Tools for rural electrification planning

Several tools are available currently on the market aiding a wide range of stakeholders in planning electrification strategies [26]. These tools address different energy planning problems emanating from one or more issues in the developing world as far as access to energy is concerned.

2.5.1 Reference Electrification Model (REM)

The Reference Electrification model is the computation model used to approach the problem of determining the least-cost electrification modes for rural electrification developed by the Universal Access Research Group at MIT in collaboration with the Comillas University in Madrid [27]. Though still in the developing stage, it has been tried and tested in India, Colombia, Kenya, Rwanda, and other developing countries and its main characteristics are:

- It works with geo-referenced data taking into consideration the location of individual loads
- Divide the clustering process into groups not to connect all the customers in a single energy system which will be analyzed individually and classified as a candidate for off-grid systems or grid extension projects
- Demand is not served as a whole avoiding production of too expensive solutions
- Takes into account some year-to-year effects in a most simplified manner to allow estimation of the lifetime performance of the system

Its main disadvantage is the lack of spatial design of the electric grid and the limited variety of energy resources are considered. REM version considers only two types of energy sources namely solar photovoltaic and diesel generator sets [27]. The results are strongly affected by the lack of wind and hydroelectric energy in the set of generation technologies. For hydropower, this is true due to its high reliability. The Reference Electrification Model does not bank on its algorithm but rather relies on a specific algorithm called Reference Network Model. Nevertheless, a lot of technical aspects are involved in the design of the grid but leave out or give less attention to the routing process. It also takes into account a few parameters such as voltage limits, capacity constraints, and continuity of supply but in the spatial aspects, it takes into account the position of lakes, natural reserves, and roads with much attention to the impact of rivers, elevation, and land cover on the network routing [28].

2.5.2 Reference Network Model (RNM)

The Reference Network model is designed by the Technological Research Institute of Comillas University and it is a large-scale planning tool. It uses GPS coordinates and the power of every single consumer and distributed energy source to do its planning. The designs of voltage networks (high, medium, low), planning of substations, and feeders can be achieved with this tool. To achieve all this it makes assumptions and considerations about technical aspects and geographical constraints [28].

RNM utilizes two available operation modes allowing design networks in greenfield and brownfield environments. The greenfield environment is used to sketch networks in virgin territories which lack any kind of electric infrastructure but design the new grid transmission substation points with distributed generation considering the interconnections of both. However, the brownfield instead is dedicated to network expansion to accommodate any additional demand [28].

Figure 11 illustrates the network built with RNM in rural areas, where the red lines are the medium voltage (MV) feeders, black lines illustrate low voltage (LV) feeders, the green triangle is the HV/MV substation, green circles are MV/LV Transformer substations and small points are LV customers.

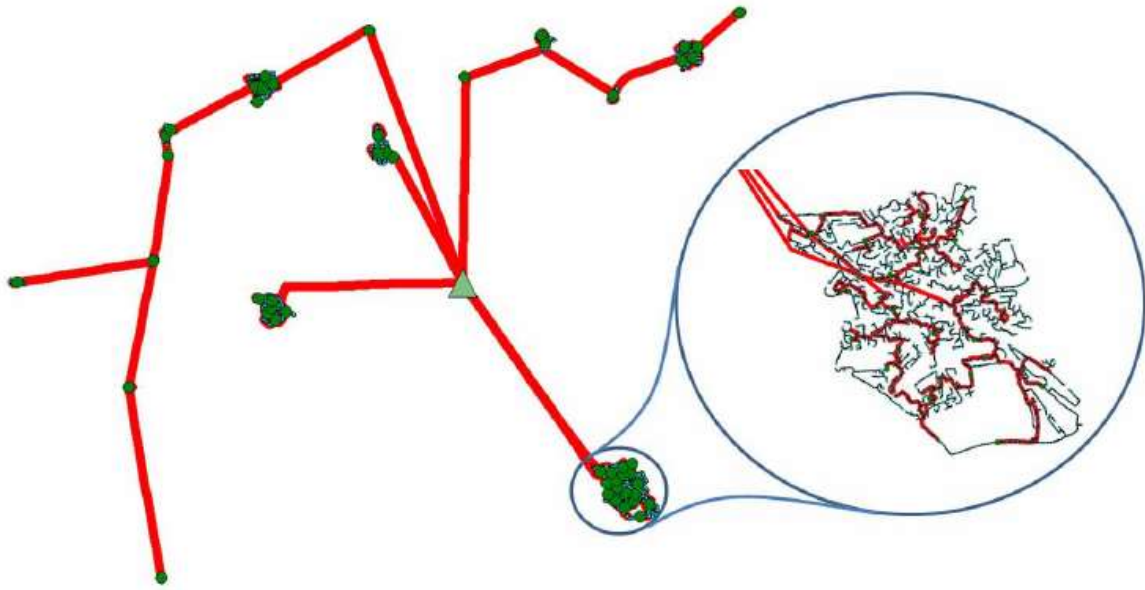


Figure 11: Example network built with RNM in rural areas (Source: [28])

2.5.3 Open Source Spatial Electrification Tool

OnSSET is the optimization energy modeling tool that utilizes the bottom-up approach to estimate, analyze and visualize the most effective electrification strategy in terms of cost [29]. It is an authentic software developed in python with an open-source license. It divides the study area into cells that are proportional to the preferred resolution [30]. It can give an outcome of the best electrification strategy either from stand-alone, mini-grid, or grid extension options. It also suggests the most suitable technology in the case of the off-grid system [31].

OnSSET does not utilize fully the layers such as the population density layer because the tool identifies populated cells during computations but does not find and deal with densely populated areas [30]. One other disadvantage is linked to power block sizing as the energy demand results from a multi-tier framework for measuring energy access does not give a real optimization due to an unrealistic load profile. Furthermore, there is no space for energy mixes due to the high degree of approximation in sizing output, and that reflects false values of Localized Cost of Energy [32]. Moreover, little space is provided for the infrastructure from both economic and technical points of view, especially in the isolated rural context.

2.5.4 Calliope

Calliope is a multi-scale energy system modeling framework that focuses on flexibility with a high spatial and temporal resolution developed by the KTH Royal Institute of Technology in Stockholm. It is a fully open-source python-based tool designed to deal with easily writable text files such as .csv and .yaml [33]. These features make it user-friendly for users without

knowledge of python and programming but most importantly make it a building block for higher-level frameworks. Though it is not working directly with GIS data its design is in such a way that it provides spatial optimization which allows the addition of key dimension components of the energy system from resources to users [33].

Calliope deals with large and small-scale optimization systems which makes it a suitable tool for micro-grid scales and multinational energy systems. The disadvantage of this tool is the fact that load flows analysis and electric power are not catered for in the grid sizing as a result one has to know the grid configuration and that limits its true potential [33].

2.5.5 Network Planner

Network Planner is the electrical network planning tool written in python that utilizes the top-down approach. It is developed by the research team from the Earth Institute at the University of Columbia for its unique decision support in exploring the costs of different electrification technology options in communities without access to electricity [1]. All the data on electricity demands and costs with population together with socio-economic information are combined to compute detailed estimates of the demand for communities in the dataset. The model compares the three electrification options and selects the most cost-effective option for electrification. This assists planners in understanding both costs and time frames for electrification and makes priorities in where the grid expansion is the best option stand-alone options are the preferred option in terms of costs [1].

2.5.6 GISEle

GISEle (GIS for Electrification) is an open-source on-development python-based tool that provides the least cost electrification solution for load connections in rural areas [15]. Its operation is simple, it chooses among on- and off-grid strategies using GIS and terrain analysis for the model study area. It uses the group loads which utilize the density-based clustering algorithm called Density-Based Spatial Clustering of Applications with Noise (DBSCAN) and uses graph theory to find the least cost electric network (LCOE) topology that is suitable to connect all the people in that particular area [17]. The whole idea is the definition of LCOE of decentralized and grid-connected solutions [34].

GISEle places itself among the available tools for electrification in a global framework where access to electricity seems to be the biggest challenge faced by the international community [34]. It is a free and open-source application that is written in Python language and allows for the improvement of new functions and changes that might be required for constant development [35]. The only limitation of GISEle is that its operation is based mainly on the topological level of the electric grid and does not consider power flow analysis, system reliability, voltage regulation, and many other aspects related to electrification planning. Furthermore, the results achieved by GISEle have some flaws as the Steiner tree solution might also not be a good representation of the hierarchical structure of the real power even though it is the least costly [15]. The computer-aided simulation of how best the combination

of different software works as GISEle is written in Python language is briefly described in the Table 1.

Table 1: The main characterization of the tools			
TOOL	DESCRIPTION	STRENGTHS	WEAKNESSES
REM	Support in electrification strategy planning	<ul style="list-style-type: none"> - GIS-based - Multi-activity - Complete Analysis 	<ul style="list-style-type: none"> - Only PV and Genset Technology
RNM	Network spatial planning	<ul style="list-style-type: none"> - The high number of aspects considered - GIS-based - Electrical balance 	<ul style="list-style-type: none"> - Low detailed routing
OnSSET	Forecasting for Energy Policy	<ul style="list-style-type: none"> - GIS-based - The separation between electrification strategy 	<ul style="list-style-type: none"> - Single-cell approach - No sizing - No hybrid configurations
Calliope	Multi-scale energy systems modeling	<ul style="list-style-type: none"> - Open-source - GIS-based - Multi-directional - Relatively high user-friendliness 	<ul style="list-style-type: none"> - Exogenous grid infrastructure
Network planner	Network planning	<ul style="list-style-type: none"> - Optimal grid planning 	<ul style="list-style-type: none"> - Only bidimensional analysis, with no morphology account - No population density Accounting - Only grid extension
GISEle	Network spatial data analysis and planning	<ul style="list-style-type: none"> - Free and Open-source - GIS-based - Detailed routing - Optimal techno-economic grid planning 	<ul style="list-style-type: none"> - It does not consider power flow, analysis, system reliability and voltage regulation

Chapter 3: Methodology

3.1 Introduction

This study is aimed at developing a complete procedure for the rural electrification strategies emanating from the use of spatial data analysis which runs through all passages that lead to the identification of an optimal techno-economic solution. The proposed approach (hereinafter named GISEle) exploits the potentialities of the GIS environment in which it operates. The following spatial characteristics of the proposed solution are considered by this approach;

- Consumer spatial distribution and generation plants;
- The existing national grid and detailed topology to connect to the grid

The spatial characteristics allow the supply of more accurate assessment on GISEle about final estimates of the costs to a possible different solution. Figure 12 is a detailed description of the method together with the algorithms constituting the procedure.

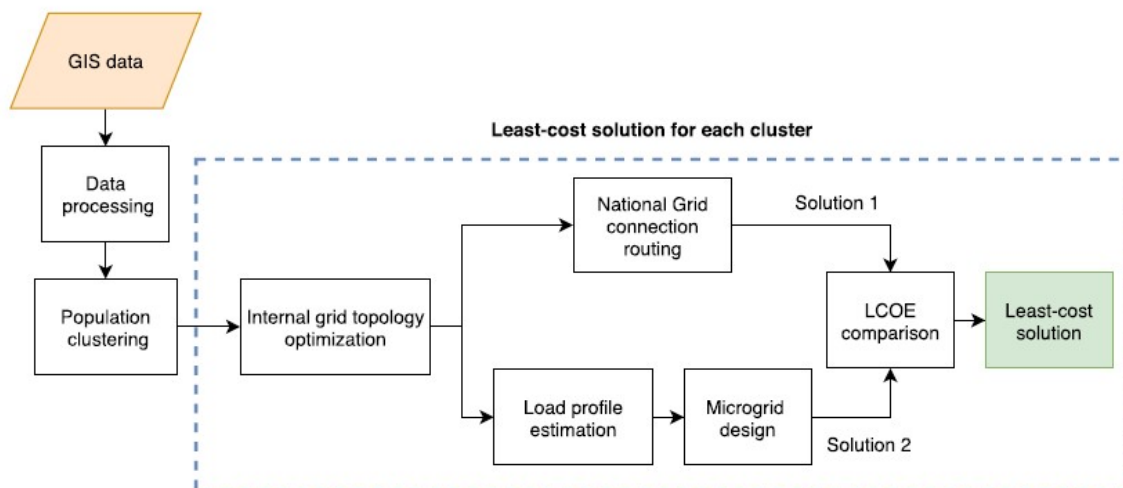


Figure 12: Flowchart of the GISEle procedure (Source: [36])

Collection of the data needed for the analysis is the first step of the procedure; information about the population density and terrain characteristics are together gathered and combined into a discrete representation of the target region. The information integrated into each point is handled to define the penalty factor index and its difficulty in building the electric line through a specific point. GISEle attains analysis on population distribution alongside the defined penalty factor.

In the population clustering step, the algorithm associated with clustering identifies the densely populated area and divides it into groups of clusters constituting independent energy for communities. The communities that are outside or that are isolated are automatically discarded and defined as the outlier. The electric lines routing algorithm designs the optimal and least-cost electric network from the combination of the information of the spatial distribution within a cluster and considers the opportunity to make a direct connection to the HV national transmission line with the calculation of costs and optimal routing path.

With defined electric infrastructure, GISEle provides the evaluation of cluster energy needs and defines the optimal configuration of the preferred system that will reliably fulfil the energy required. Lastly, GISEle provides economic analysis on whether the possible electrification strategy will be an Isolated Mini-Grid or Grid-connected energy system by evaluating the cheaper solution by comparing the respective values of LCOE. In this study the new GISEle is developed which will only focus on solution 1 and discard the second solution to meet the primary purpose of this study.

The GISEle procedure described above is made using Python programming language and deploys different applications such as web development, data science, artificial intelligence, and machine learning which are selected mainly on three characteristics suitable to GISEle goals and aspirations as follows:

- Python is flexible and works well with different operating systems available and can easily be integrated with third-party software such as QGIS.
- The library has a wide range of packages that the selection can be made from
- Useful tools dealing with big databases and GIS information are offered by Python which is the core of GISEle's procedure

The most important packages that are used in GISEle development are briefly described:

Pandas

Pandas are designed for data manipulation and analysis and are one of the best software libraries written specifically for Python. Specifically, data structures and operations for manipulation of tables and time series are offered and it allows the importation of data from various file formats such as comma-separated values (csv), other data manipulation such as merge and data cleaning such as filling and replacing.

Shapely

The manipulation and analysis of planar geometric objects utilize this package and it is very useful in dealing with GIS vector layers and polygon shapefiles which play a major role in GISEle's routines and outputs. Nonetheless, it ignores complex data formats such as three-dimensional shapes or coordinate systems.

Geopandas

The combination of the capabilities of the above packages is done by geopandas to facilitate a working environment with geospatial data by extending data-frames used by Pandas while also achieving a high-level interface to multiple geometries to shapely making it the most favourable tool to manage GIS data [22].

NetworkX

This is the last package used to create, manipulate and study structure and functions together with dynamics and functions of complex networks. It allows the computation of the Steiner tree and graph manipulation which is the main aspect of the graph theory and it is used mostly by grid routing algorithms executed by GISEle [37].

The python coding routing algorithm procedure is illustrated in Appendix 1 showing all the steps from data processing to the final grid routing of both LV and MV grid networks for all 10 villages of the selected study area.

3.2 Data Gathering

All data needed for the analysis of electrification strategies is collected as the first step of this procedure. Datasets with different levels of details available from internet platforms are normally used for the collection of spatial data. The World Bank Group together with several partners has launched an open data platform developed for governments, development organizations, academia, non-governmental organization, civil society, and certain individuals for sharing of data and analytics in a call to achieve universal access to modern energy services [38]. Governments, the private sector, and development partners collect data every day to inform, prepare and enforce policies and investments. Nevertheless, gathered data remain locked when reports are made public, especially high-quality data that requires significant investment. However, underdeveloped countries do not have digital datasets at all.

Since it is not easy to find all data, especially high resolution, they are made available only for a certain fee. The published list on the OnSSET website for available platforms exploited by GISEle is listed in Table 2 for the activities described in this methodology with additional information about the data classification: raster and vector. They also define the target area which addresses the GISEle analysis.

Table 2: Geo-Spatial datasets for GISEle procedure (Source: [36])	
DATASET	TYPE
Population density	Raster
Administrative boundaries	Vector Polygon
Existing grid network	Vector line
Electric substations	Vector point
Roads network	Vector line
Water boundaries	Vector Polygon
Land Cover	Raster

Datasets obtained normally do not fit the target area perfectly as some of them contain global level information whereas others cover only part of the area of interest hence multiple files must be combined. Likewise, the administrative boundaries layer is utilized to clip each dataset as a mask to obtain information fitted to the desired area of interest.

3.3 Data Processing

All input data are combined and processed into a single input file using GIS applications such as QGIS, open-source software or ArcGIS, which is commercial software. The grip of points must be created first that covers all studied areas with a specific distance between each point. The GISEle resolution analysis is defined by this distance. The most important aspect of the

methodology is resolution as it has to be selected according to all data collected and find a suitable number. Raster layer resolution can achieve high numbers as the technology from satellite imagery is much higher. The preferable resolution is between 100 meters and 1 kilometre as the number of points to be processed below these points is too high to be processed and could become too complex as accuracy above this range can also be impaired [15].

The resolution of 1 kilometre for Low Voltage (LV) lines can already be impairing as grid routing through small streets is required as each detail is important. For High Voltage (HV) grids spatial detail is not necessary as it usually covers long distances. A resolution of 200 meters for HV could be very complex and unnecessary [15]. The grid point with the resolution of 1 kilometre around a small village is depicted in Figure 13. Only two points are inside the village and indicate the expected results of the grid routing which is anticipated to be a straight line crossing the whole village while using this resolution. Due to the low resolution, houses can not be seen, the information is not sufficient enough to represent an LV grid of which it ought to follow the village roads to connect each house.

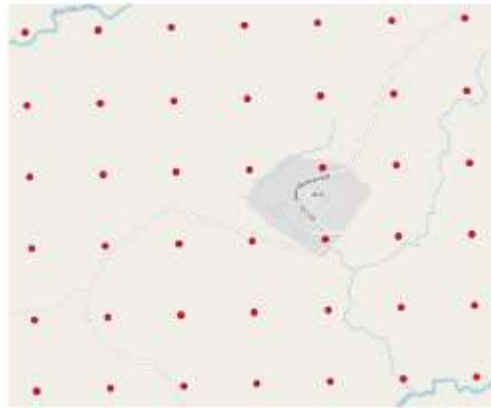


Figure 13: Grid of Points with a resolution of 1km (Source: [36])

All the input layers now have to be associated with each point of the grid after the creation of the grid of points and the selection of the appropriate resolution. Layers such as elevation layers which are raster layers can use a sampling function. The sampling raster values function allows the grid of points created to use the raster layers and add its attributes to it. Other layers such as population, slope, and land cover are represented as raster layers generally. Polygons can be used to represent the population density in which functions such as join attributes can be used to add their values to the grid of points. Lastly, distance from each point of the grid to the nearest road is the last element accounted for computation of the weight. Through the support of GIS software, the function can compute the distance to the nearest line vector later from a point vector layer. Figure 14 illustrates the procedure.

On completing all data processing and merging into a single layer file called shapefile, it is exported as a table of attributes of every point in the grid as illustrated in Appendix 1. The table in Appendix 1 represents each row as a point of the grid and then represents each column as associated information relating to the point of its population, elevation, and other

related data gathered. Another file must also be created that contains the information of the available substations for connection. It is a simple file where each point represents a substation and its type whether is a high voltage, medium, or low voltage respectively.

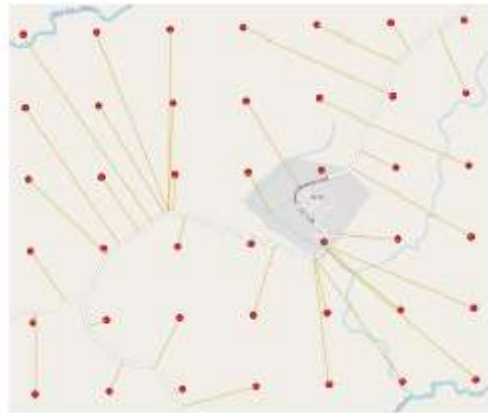


Figure 14: Distance to the nearest line function (Source: [36])

The cost of connection and power limit is assigned for each type and combined into a single file (shapefile) that is exported as a table forming two input files required by GISEle. Other additional input parameters such as Coordinate Reference System (CRS), resolution, line base cost, population threshold, and load per capita are required by routine. Resolution is used to create the grid of points and the CRS of the gathered GIS information. Line base cost on the other hand is used to compute the cost of the electric line that will be utilized whereas the population threshold distinguishes and identifies the number for each node that the algorithm will use for creating the cluster grid. Lastly, the load and size of the electrical cables required are estimated through the load per capita parameter. A summary of all the input information is listed in Table 3.

Table 3: Summary of input information to GISEle		
Grid File	Substation File	Parameters
Point Identification (ID)		
Point Coordination (X, Y)	Substation Identification (ID)	Resolution [m]
Population	Substation Coordinates (X ,Y)	Coordinate System (CRS)
Elevation	Substation Type	Line base cost [£/km]
Slope	Power limit for connection	Population threshold
Land Cover	Extra cost for HV connection	Load per capita [w]
Distance to the nearest road		

3.4 Weighting Process

GISEle performs the weighting strategy of the input grid of points as its first process. The cost of electric line realization is impacted by information gathered and embedded in each note which constitutes a set of spatial aspects. Depending on their values they contribute to a

different extent increasing the line cost per unit length concerning the ideal condition. Not all technical and geographical aspects have been taken into account inside the analysis as many of them are important in HV transmission line planning but negligible for MV lines. Therefore, costs connected to interconnection communication lines, direction change, and icing problems are neglected. The methodology combination of Monteiro and the penalty strategy used in the OnSSET tool is the best-considered approach [39]. The penalty factor representing the base cost is increased according to the characteristic of the weighted point. That is the total penalty factor summation is assigned to each characteristic of the grid points given by slope, land cover, and distance to the nearest road.

These values are analyzed and together combined to return a penalty factor coefficient that affects the electric line running through it. Every single voice contributes to the initial set point of equation 3.1 for the penalty factor to respond to the question of “how many times more than the basic would cost my electric line?”

$$\text{Penalty factor} = 1 + \sum_{i}^{\text{penalty aspects}} \text{penalty}_i \quad (3.1)$$

Materials for the construction works which include tools to be utilized when implementing the design are all brought to the site through roads hence roads are very crucial for logistics. The roads are normally constructed to accompany the work if they lack as the cost of connections is higher if the point is far from the road network. Nevertheless, the limit is set to equal 6 times the basic costs of the connection and 1km from the road as depicted in Figure 15 which shows its profile is reached.

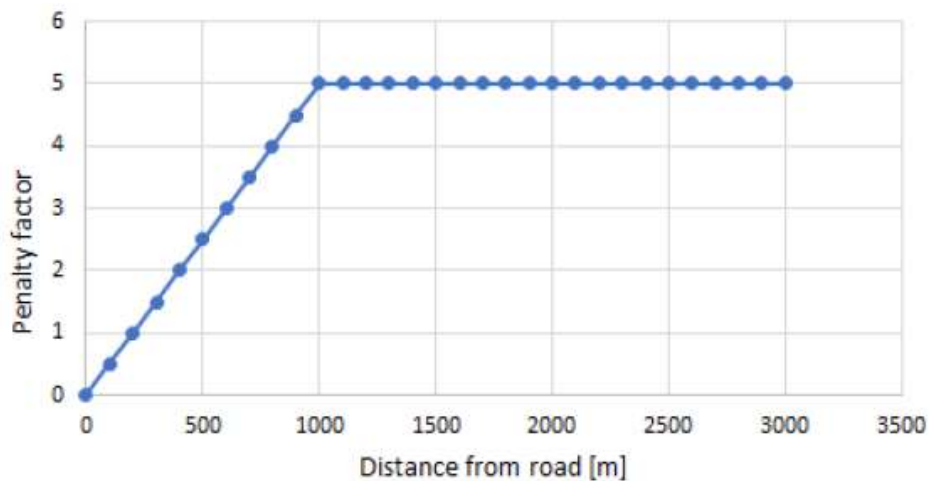


Figure 15: Penalty factor vs Distance from the road (Source: [15])

The steeper the terrain the harder the electrical reticulation as the slope penalty has an exponential profile. The design of exponential curve is designed in such a way that the slope of 35 degrees returns a value of 1 as depicted in

Figure 16. Road proximity is very crucial and must be underlined but does not matter if the road is close to the site. The penalty factor equals 1 if the road distance is greater than 100m.

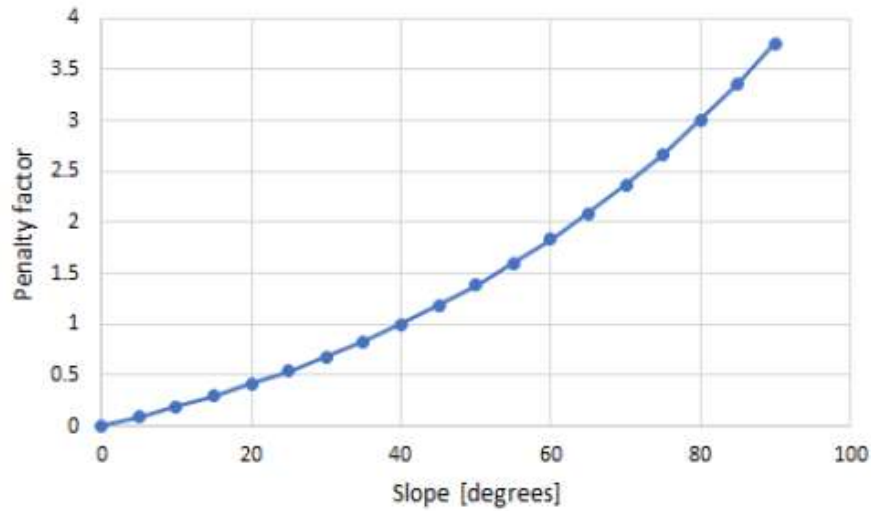


Figure 16: Penalty factor vs Distance from the Slope (Source: [15])

3.5 Clustering

The next step after the collection and processing of data consists of population clustering and electric loads of the entire area. The population attribute of the previous regular points grid created have to be considered in pursuing this process. The algorithm goes through the entire target area to find the densely populated area that suits the electrification. Each cell is considered by itself in the basic approach hence the main objective of this clustering process is to move away from the basic approach. The strategic value of closely located populated areas is neglected by the algorithm but rather proceeds with the identification of valuable groups of cells instead of only one at a time. There are criticalities in this top-down approach:

- Highly populated areas in the remote rural areas are sometimes not formally recognized as yet;
- Knowing the population of the desired area is just not enough for adequate design as the population density can vary from time to time.

Moreover, population clustering is one important GISEle procedure that reduces the computational stress of our model. Nevertheless, the high number of points to be considered by the applied routing procedure would require a huge amount of time but clustering solves these issues by classifying isolated points as an outlier and grouping all others in different clusters. Furthermore, the routing algorithm will then be applied to each cluster by drawing its specific electric topology. In terms of computational time clustering algorithms outweigh routing algorithms as they are fast and speed up the global procedure.

GISEle design is a bit different from the other models in the literature review as the specific methodology had to be adopted. The selection was made after comparing the two best clustering categories which are discussed and considered suitable approaches for GISEle model purposes:

- Graph-based class: this is the first choice in the development process considering our specific goal. The idea was to create a unique grid and delete the worthless path as the final purpose of solving the electrical grid routing problem. Likewise, the clustering

algorithm is much more efficient than the routing algorithm which is the problem that brings or separates the two steps to allow the first one to reduce the computational time of the second one.

- Grid-based and Density-based clustering algorithms: these are the most preferred options as they are quite similar but easy. the grid-based clustering performed on raw data is considered for the previously detailed data gathering and processing step as the space is partitioned in the grid-like structure. For the sake of simplicity, each cell's attributes are collapsed into a central point.

Consequently, GISEle's clustering algorithm is a modified version of DBSCAN and a density-based algorithm based on input data property. General clustering problem points represent a singular element and this algorithm is different in that it has a fundamental property which is the population. The particular adaption in which the population attribute is the point weighting criterion now that the DBSCAN algorithm is selected is implemented. It firstly allows the creation of clusters with exact community extension shapes and neglects vast zones with few people but only prioritizes highly populated zones [17]. Nevertheless, the main weakness of this algorithm as stated does not affect the suitability of this algorithm for our purpose as it does not affect the final electrification status of a point.

Finally, the user has a preference for choosing combinations to be entered in GISEle as clusters are created and the model asks the user to combine output clusters based on a graphic interface showing their distribution in the space.

3.6 Electric grid routing

3.6.1 Creating a Path

In this step, the main idea is to create an electrical grid connecting populated points inside each cluster. The first step is to transform the input weighted grid of points into a graph of $G = (V, E)$ where equation 3.2 is used to calculate each edge weight connecting two vertices u and v .

$$C_{u,v} = L_{u,v} \times BC \times \frac{p_u + p_v}{2} \quad (3.2)$$

Where:

- C_u is the connection cost of the vertices u and v in Euros (£);
- L_u is the distance in kilometres between u and v ;
- BC is the base cost of the electric line in [£/km]
- p_u and p_v are the penalty factors assigned to vertices u and v .

Depending on the type of line to be utilized the base cost of the electric line as one of the input parameters must be estimated by the user. The 8 neighbouring points of point u as depicted in Figure 17 are all the points at a distance smaller than the length of the grid and it is given by equation 3.3

$$d_{u,v} \leq \sqrt{2} \times \text{resolution} \quad (3.3)$$

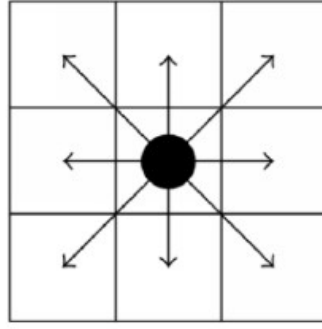


Figure 17: Eight neighbours with edges between one point (Source: [40])

[3.6.2 Steiner tree creation](#)

The NetworkX is a Python package that allows the creation, manipulation, and study of the structure, dynamics, and complex network functions. One of its characteristics is the ability to provide an approximated Steiner tree by computing the minimum spanning tree of the sub-graph of the metric closure induced by terminal nodes T . The function asks for the Edge of the cost matrix previously computed which is the weighted graph $G = (V, E, w)$ and terminal nodes that must be connected. All the populated points inside the cluster being analyzed are referred to as terminal nodes or the points in which the population is higher than a set threshold. The approximated solution gives a Steiner ratio (r) by equation 3.4 which varies from 1 in a real simple tree to 2 which is a high amount of terminal nodes.

$$\rho = 2 - \left(\frac{2}{T} \right) \quad (3.4)$$

Two data sets are being processed which are weighted graph G and terminal nodes T . weighted graph G contains information about all the points of the initial input grid while terminal node T contains the information about only the populated points of a given cluster. At higher resolution, the computation becomes complex as a big data set G requires a huge amount of time and for that reason only assigned points to the cluster being analyzed are selected. Figure 18 illustrates the results of GISEle's routing in which:

- Computed Steiner tree is represented by green lines;
- Terminal nodes are represented by red points
- Blue and yellow are points belonging to two clusters;
- The whole input weighted grid of points is represented by brown points;
- The darker area represents the outside of the studied region for electrification.

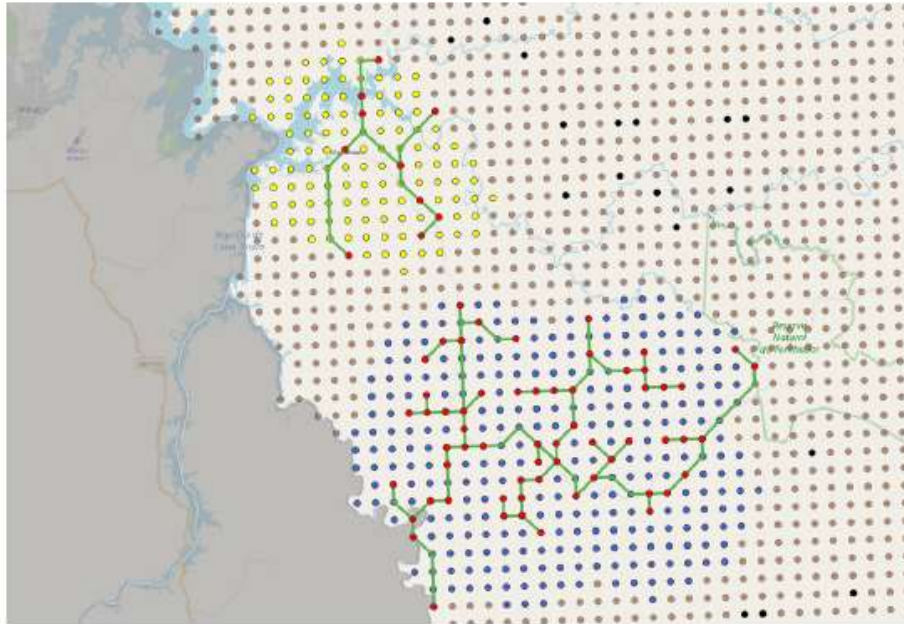


Figure 18: Two different clusters for a resolution of 1 km steiner tree approximation
(Source: [16])

3.6.3 HV/MV Substation connection

For the creation of the connection of substation to be possible to the existing national grid from the separate energy community, two factor needs to be taken into consideration as all available substations are evaluated.

I. Distance to the substation

Since the cost of an electric line is proportional to its length this factor is straightforward. It is apparent that between the two substations of the same type the closer one should be chosen for connection to reduce cost. The computation of the distance among each cluster point is done for each substation and then assigned to the one with the lowest distance for connection. The computation considers only the substation that is near unless other factors such as the type of substation are taken into consideration.

II. Type of substation

A suitable substation must be selected for connection depending on the amount of population which normally translates to the amount of load required. It may not be practicable to connect say a nominal power of 5kW to an HV/MV substation as the costs of deploying the new MV line, protection relays, and new transformer zone do not offset the gain in electrifying the small community. However, technical specifications and requirements for connection to HV substations are strict and have to be adhered to. Nevertheless, the low-power MV substation cannot be utilized for a bid cluster with a dense population which normally translates to a heavier load hence the connection to an alternative substation will be necessary since the connection to the nearest is technically impracticable.

These two factors' evaluation is very important and recommended as GISEle uses other information tabulated in Table 3 to complete all the analysis. Equation 3.5 defines the load per capita as it is utilized to compute the total amount of load required by each cluster grid;

$$C_{Load,k} = \sum_T P_T \times LpC \quad (3.5)$$

Where,

- $C_{Load,k}$ is the total load or the cluster k ;
- P_T is the population of the terminal load T ;
- LpC is the load per capita parameter.

GISEle assigns the most suitable substation to each cluster k based on the total amount of C_{Load} and substation input file defining the power limits for connection using the procedure illustrated in the flowchart of Figure 19.

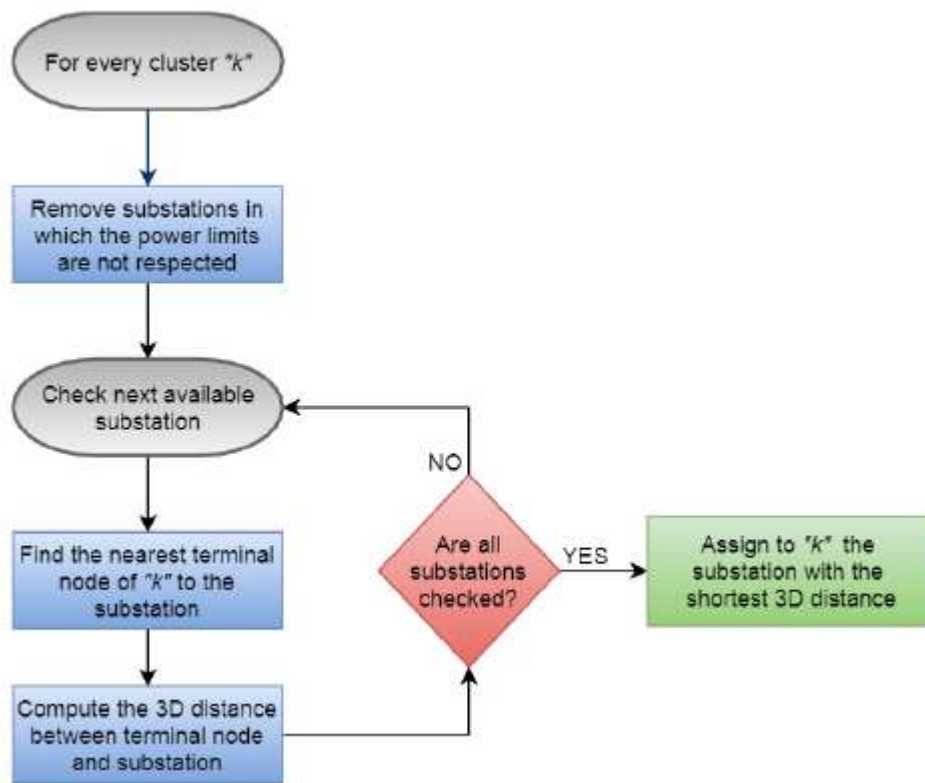


Figure 19: GISEle's substation flow chart assignment (Source: [16])

The following steps summarize the procedure shown in Figure 19:

- I. If $C_{Load,k}$ from available all available substation is outside the power limitations range those substations are removed;
- II. Find the remaining substations by finding the nearest terminal node of cluster k and do computation on the 3D distance between the substation and the nearest terminal node.

III. The substation that has the shortest 3D distance is assigned to cluster k.

Each cluster is identified by this procedure as a terminal node and a point of connection to the national grid. The Steiner tree algorithm is not necessary to connect only two of these points as it becomes the shortest path problem rather Dijkstra algorithm is convenient because is faster. NetworkX as another Python package allows for computation of the shortest path between a source point and target point through a weighted graph $G = (V, E, w)$. The first step is to create the edge cost matrix similar to the Steiner tree case on the input grid of the points file. On contrary, it is not possible to use the point inside the cluster as the substation will be outside of the clustered area. One other way of reducing the size of G and computation stress is by introducing the selective box which encompasses all the points between the target with margin and the source as illustrated in Figure 20.

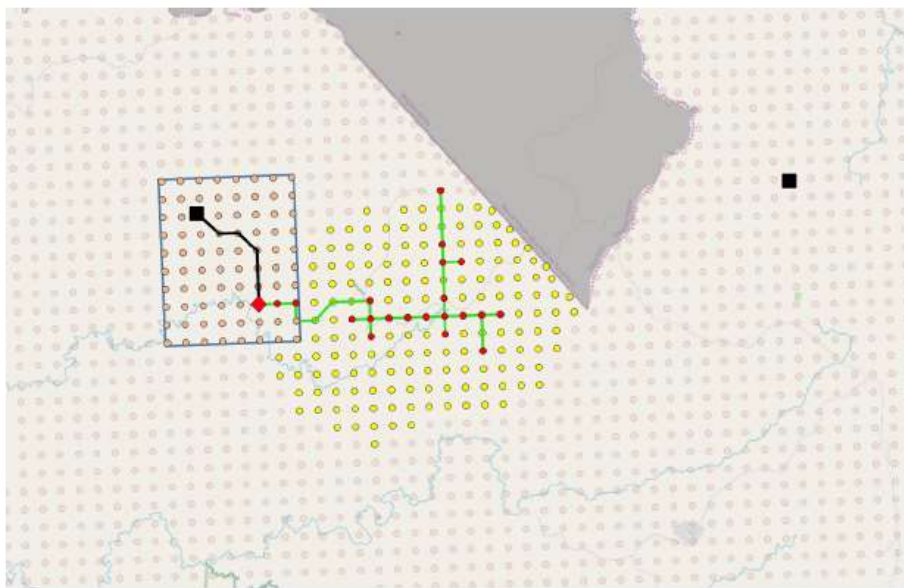


Figure 20: Box selecting only points between target nodes and source (Source: [16])

To relieve the computation burden and allow for a faster shortest path the number of points G has to be reduced by considering the points inside the box. The box is computed by the use of coordinates of the source and target node with the addition of extension based on the distance between them. The selective box can also be catered for in the Steiner tree computation and can be achieved by using a cluster that has a non-convex shape which possibly would require a path that would go outside of the cluster instead of using cluster points. An example of the substation connecting algorithm for two scenarios, different clusters, and different types of a substation where HV is represented in black squares and MV in red squares are shown in Figure 21.

Both clusters fall into the power limitations categories in this scenario where the bigger cluster which is represented in blue is too much loaded to be connected to the MV substation even though it is much closer but the algorithm decides to connect to the HV substation because of the power limitations factor being taken into consideration. On the other hand, the green cluster is not much loaded hence it would be costly to connect to the HV substation rather than connecting to the nearest MV substation.

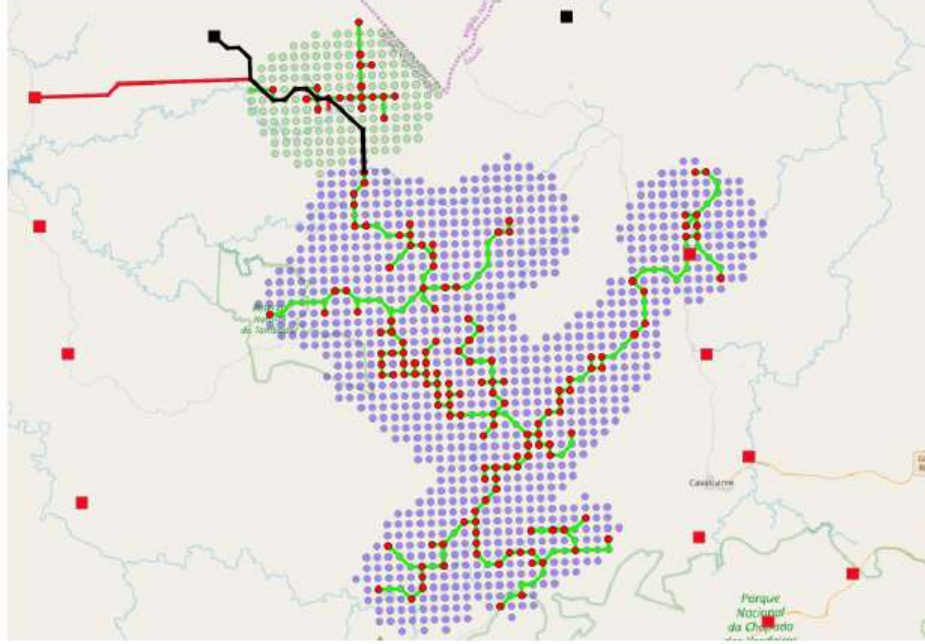


Figure 21: Substation connecting algorithm (Source: [16])

Finally, an LCOE analysis is made to decide whether the grid solution is economically viable concerning creating a connection to the existing distribution grid. The LCOE of the grid solution connecting the cluster and distribution grid is obtained using equation 3.6

$$\text{LCOE}_{\text{on-gr}} = \frac{C_{\text{grid}} + C_{\text{con}}}{E_{\text{total}}} + \text{COE} \quad (3.6)$$

Where,

- $\text{LCOE}_{\text{on-grid}}$ is the Levelized Cost of Electricity
- C_{grid} is the capital cost of the cluster's internal electric grid.
- C_{con} is the capital cost of the connection between the cluster and the existing grid.
- E_{total} is the total energy forecast of the total amount of energy produced and sold by the energy system within 25years of operation.
- COE cost of electricity of the local Distribution System Operators (DSO)

The procedure described in this chapter represents the combination of the main idea behind GISEle in its conception. Access to electricity is one big challenge faced by the whole global community and GISEle places itself among the best tools for electrification planning in fighting this global need of lack of access to energy. GISEle is a free and open-source application that allows the possibility of the development of new functionalities and improvements. Likewise, other features that were limitations as it previously worked only on a topological level such as power flow analysis, system reliability, voltage regulation, and power flow analysis have been incorporated into the newly developed GISEle interface.

3.7 Case Study

The procedure will be tested on the real case study of 10 villages in the north of Lesotho selected randomly from the previous study conducted (Electrification Master Plan – [41]) as

highlighted in yellow in Figure 22. Villages 29 and 30 are excluded from the study as they seem to be falling outside the community councils that are much closer to each other which will make this study more viable in terms of the cost of electrification. The villages are classified under the Enumeration Area Code and sub-divided into urban, peri-urban, and rural settlements. The selected villages are unelectrified but it is a government plan to extend the distribution network to those villages. Figure 22 is a breakdown list of the highlighted enumerator codes for the villages.

YEAR 1				YEAR 1			
PRIORITY	EA CODE	DISTRICT	COST [M]	PRIORITY	EA CODE	DISTRICT	COST [M]
1	06600443032	Mohale's Hoek	1,575,000	28	05480113026	Mafeteng	1,680,000
2	10730233004	Thaba-Tseka	1,125,000	29	01020213001	Botha-Bothe	1,230,000
3	02171012017	Leribe	1,365,000	30	01020213034	Botha-Bothe	1,725,000
4	10750432074	Thaba-Tseka	1,905,000	31	04440712034	Maseru	1,275,000
5	09800433015	Mokhotlong	1,605,000	32	05520512037	Mafeteng	1,605,000
6	03260713038	Berea	1,365,000	33	02090413019	Leribe	1,605,000
7	05520512031	Mafeteng	1,200,000	34	08700243037	Qacha's Nek	1,620,000
8	01010123024	Botha-Bothe	2,475,000	35	05510412034	Mafeteng	2,865,000
9	06600443043	Mohale's Hoek	1,500,000	36	07640641015	Quthing	1,230,000
10	01040413033	Botha-Bothe	1,815,000	37	04450813057	Maseru	1,230,000
11	07640641022	Quthing	1,575,000	38	05530613024	Mafeteng	1,740,000
12	03210313042	Berea	1,245,000	39	03250613017	Berea	1,560,000
13	06590343042	Mohale's Hoek	1,695,000	40	05510413047	Mafeteng	1,290,000
14	06560113027	Mohale's Hoek	1,635,000	41	02171013029	Leribe	1,725,000
15	03260713036	Berea	1,200,000	42	04420513079	Maseru	1,380,000
16	02120713027	Leribe	1,980,000	43	02110613009	Leribe	1,620,000
17	03190123022	Berea	1,290,000	44	02120713034	Leribe	1,965,000
18	02080313009	Leribe	1,065,000	45	03260713057	Berea	1,410,000
19	02060133022	Leribe	2,340,000	46	02060133053	Leribe	1,785,000
20	02100513021	Leribe	2,565,000	47	02060133054	Leribe	1,560,000
21	08710333024	Qacha's Nek	1,260,000	48	10740631016	Thaba-Tseka	2,610,000
22	01010123043	Botha-Bothe	1,095,000	49	01010123025	Botha-Bothe	2,070,000
23	07650641010	Quthing	1,695,000	50	06600443031	Mohale's Hoek	1,860,000
24	06590343024	Mohale's Hoek	2,115,000	51	08690142057	Qacha's Nek	1,575,000
25	02090413040	Leribe	2,160,000	52	02080313017	Leribe	1,875,000
26	04440712035	Maseru	1,545,000	53	06590313008	Mohale's Hoek	1,575,000
27	02080313021	Leribe	1,380,000	54	06560113012	Mohale's Hoek	2,190,000

Figure 22: Villages and cost estimates from Electrification Master Plan (Source: [41])

Table 4: Un-electrified villages				
Priority	EA Code	Community Council	Villages	GPS Coordinates
8	01010123024	Makhunoane 1	Ha Morake	28°38'56.04"S 28°27'22.679"E
			Ha Poosho	28°38'51.36"S 28°26'55.679"E
			Ha Potjo	28°38'34.44"S 28°27'36"E
10	01040413033	Ts'a-Le-Moleka	Ha Selomo	28°46'26.76"S 28°20'36.599"E
			Mothae	28°46'50.52"S 28°21'1.08"E
22	01010123043	Makhunoane 2	Ha Jane	28°42'30.96"S 28°29'52.44"E
			Ha Katsi	28°42'24.12"S 28°31'41.88"E
			Phallang	28°42'46.08"S 28°31'51.959"E
49	01010123025	Ntelle	Sheeshe	28°39'1.08"S 28°24'7.92"E
			Mokoetlaneng	28°38'48.84"S 28°24'21.239"E

Chapter 4: Results and Discussions

The rural administrative place of Butha-Buthe in the northern region of Lesotho has been identified and 10 villages were selected to effectively test and interpret the performance of the GISEle methodology by elaborating on spatial data to provide optimum electrification planning. The results for each step produced for the procedure are presented below.

4.1 Data gathering and processing

4.1.1 Population Density

Data was collected as the first step for the analysis of the electrification strategy and databases such as WorldPop [42], as one of the available open data platforms on the internet, were used to collect the population data layer as illustrated in Figure 23. The dataset was then clipped using the administrative boundaries layer as the reference that was developed after the selection of the study area of 10 villages of Butha-Buthe district to only obtain information for that specific area of interest using QGIS software.



Figure 23: Population Density for villages of Ha Morake, Ha Poosho, Ha Potjo – Makhunoana 1 Community Council

The population density layer is one of the most important inputs for GISEle as through this information, the algorithm performs cluster analysis and selects which areas should be electrified from which points of connection, where the new electric grid should pass, and where the transformer should be located to accommodate all the consumers. Figure 23 illustrates the community council of Makhunoana 1 which consists of three villages of Ha Moroke, Ha Poosho and Ha Potjo as consolidated in the population census report. The estimate is the total number of people per grid-cell and is in the GeoTIFF format at a resolution of approximately 100m at the equator. It is also projected in the Geographic coordinate system (WGS84). The population density is presented in the form of shaded areas where the shading is dense signifies more population around that area. For the village of Ha Morake, the population seems to be gathered on the north and central side of the village

boundary and a bit in the southeast. Ha Phoosho population is more on the western side and southwest of the village demarcations. Moreover, the Ha Potjo population is found on the central site of the village demarcation and a bit on the southwestern side.

The community council of Ts'a-Le-Moleka consists of two villages of Ha Selomo and Mothae and the population density layer is illustrated in Figure 24. Ha Selomo seemed to be more balanced as far as the population sharing on the demarcation whereas for the village of Mothae, the more populated area is on the western side and more on the southern side of the village demarcation. The population set up from Figure 24 implies that the more the population, the likely direction the routing will concentrate on as it will also be cost-effective for the reticulation to be where people will tap electricity more easily that where there are no people to supply electricity to.



Figure 24: Population Density for villages of Ha Selomo and Mothae – Tsa-Le-Moleka Community Council

Makhunoana 2 is the community council which consists of the villages of Ha Jane, Ha Katsi and Ha Phallang, and the input population density layer to GISEle is illustrated in Figure 25 for processing. From the figure, some of the villages fall outside the scope hence the population density input layer for villages falling outside the scope will not be utilized in the input processes. This is done to give clear and correct estimates of the costs as compared to the data analysis in the electrification master plan [37] done by others which is the reference of this optimization project. The Ha Jane village population is more centred on the southern side and northern side. This village population setup already gives the picture of how the routing will come out. The reticulation will be concentrated along the demarcation side for optimal electrification. Ha Katsi village population is more concentrated on the central side and along the southwestern side. Ha Phallang population density is evenly scattered around the village demarcations but more concentrated on the central side.



Figure 25: Population Density for villages of Ha Jane, Ha Katsi and Ha Phallang – Makhunoana 2 Community Council

The last population density input was for the Ntelle community council which comprises the villages of Sheeshe and Mokoetlane as illustrated in Figure 26 to make 10 villages in all for this study. The Mokoetlane village population arrangement is more on the south and western side whereas the population arrangement for Sheeshe is more or less evenly scattered around the village demarcation.

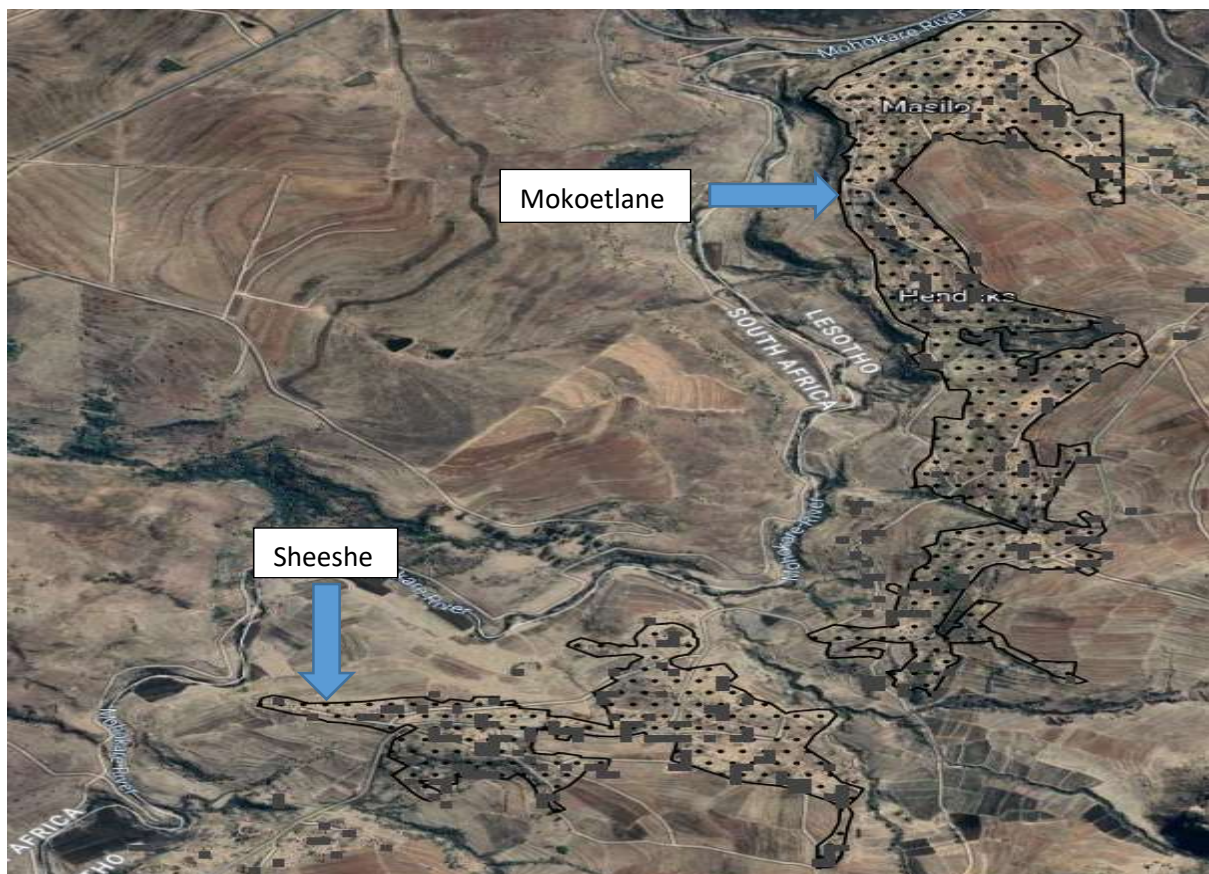


Figure 26: Population Density for villages of Sheeshe and Mokoetlane – Ntelle Community Council

4.1.2 Land Cover

The other important input layer sourced from Google Maps as one dataset from the internet is the land cover which consists of waterways and land use as illustrated in Figure 27 for the community council of Makhunoane 1 which comprises villages of Ha Morake, Ha Poosho, Ha Potjo. The orange shapes depict the houses which GISEle will use to determine the amount of power needed to supply each village. This input is also helpful for the routing process as the reticulation needs to be near to the points of supply for the community to tap with minimized cost. The yellow patches depict the land covered with indigenous vegetation which is only considered reserved by GISEle like Cheche. Moreover, the red lines depict the waterways and dongas, this also assists in planning to route far away from the waterways to protect the infrastructure and to make it easier to access for operation and maintenance.

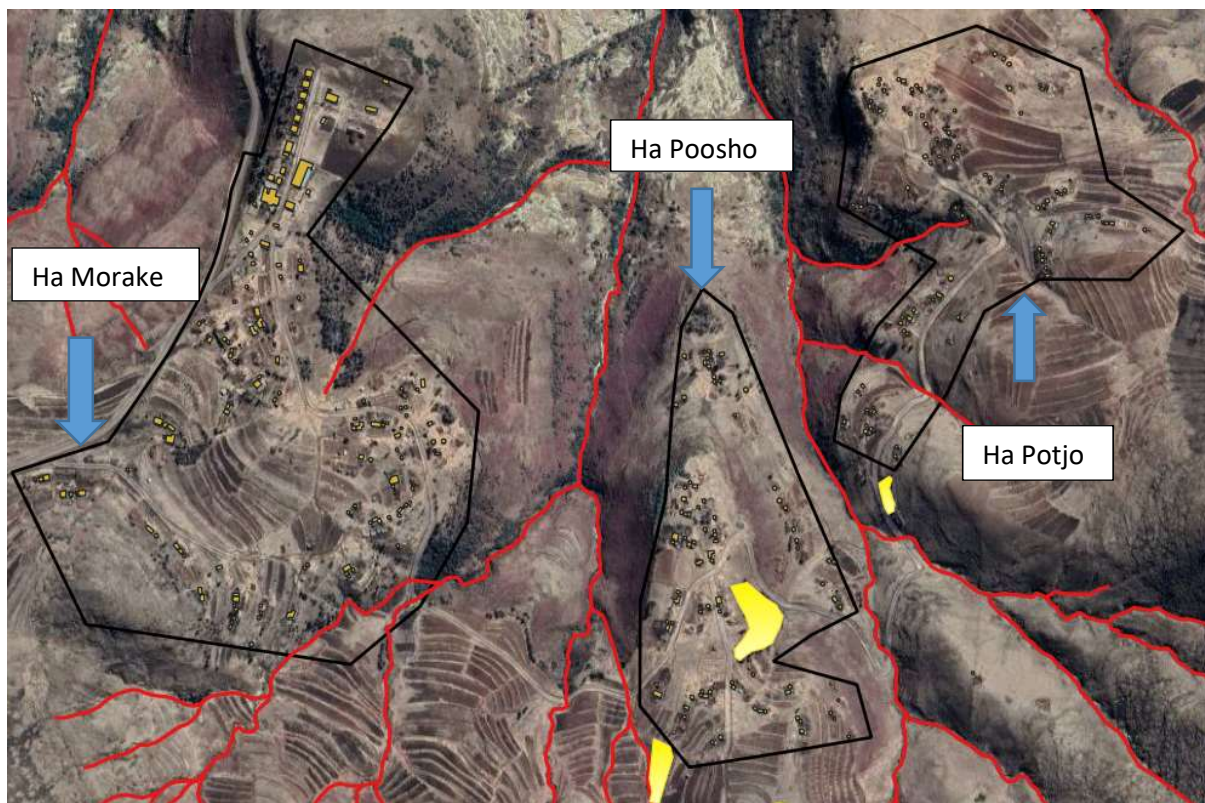


Figure 27: Land cover for villages of Ha Morake, Ha Poosho, Ha Potjo

The next land cover input layer, showing the landcover of the Ts'a-Le-Moleka community council is illustrated in Figure 28 which comprises the villages of Ha Selomo and Mothae. The yellow patches highlighted represent the vegetation which must be taken into account when the routing processes select the appropriate location for the electrical reticulation. The lines that are highlighted in red represent the waterways and dongas which they must also be avoided in the selection of suitable areas for routing.

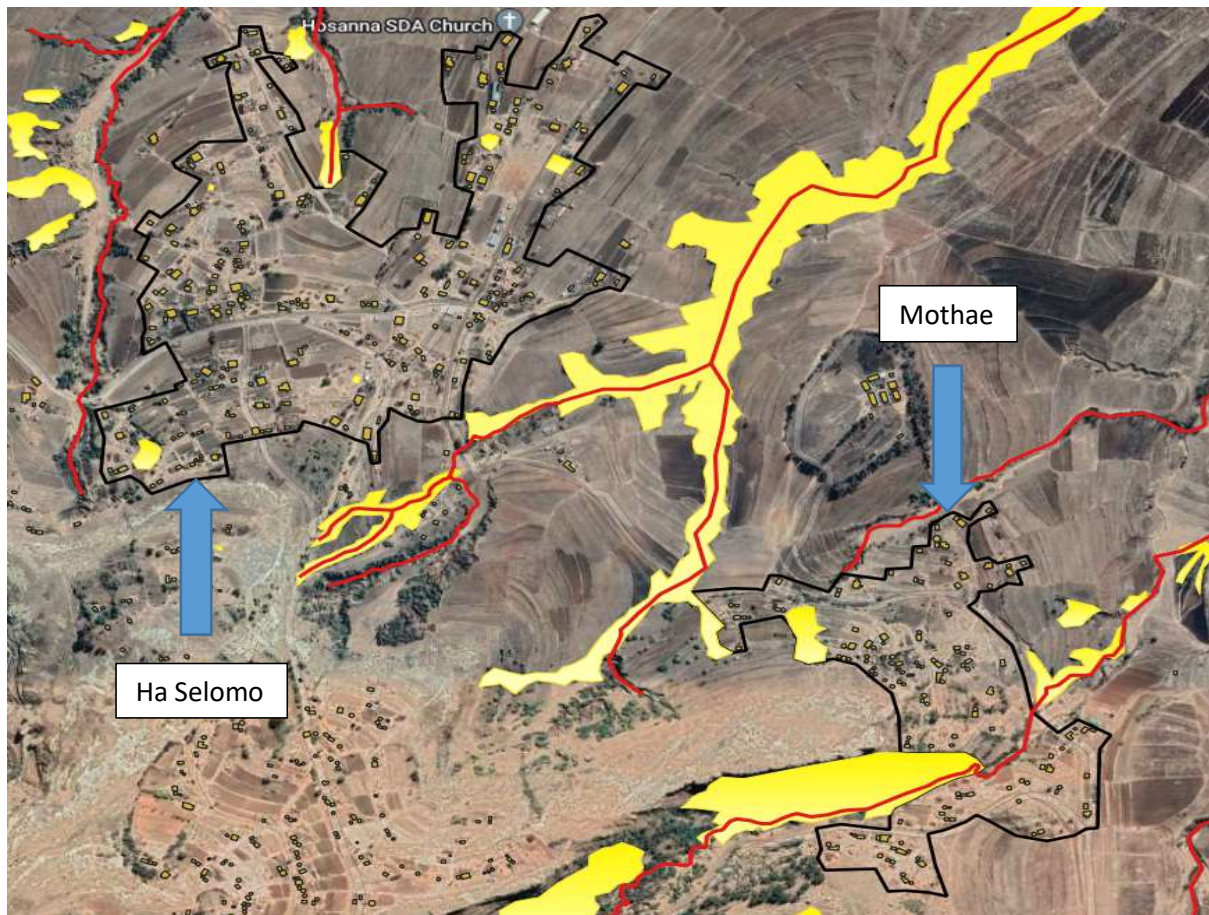


Figure 28: Land cover for villages of Ha Selomo and Mothae

The land cover for the community council of Makhonunoane 2 is illustrated in Figure 29 and GISEle only populated the earmarked villages and left out the other neighbouring villages as the whole idea is to compare the costs of electrification using GISEle versus other planning tools used in previous studies in which case the reference is the Electrification Master Plan. The areas highlighted in yellow are the natural plants which must be taken into account and be protected when planning the reticulation for these villages. Ha Jane village is more on the high hills hence there are not many waterways and natural plants to protect which makes it easy for the algorithm to do routing.

The land cover input layer for the Ntelle community council is shown in Figure 30 where the red line represents the waterways and gullies, the area highlighted with yellow colour is the natural plants that need to be protected and cannot be tampered with or rather need to be avoided when planning the electrical reticulation.



Figure 29: Land cover for villages of Ha Jane, Ha Katsi and Phallang

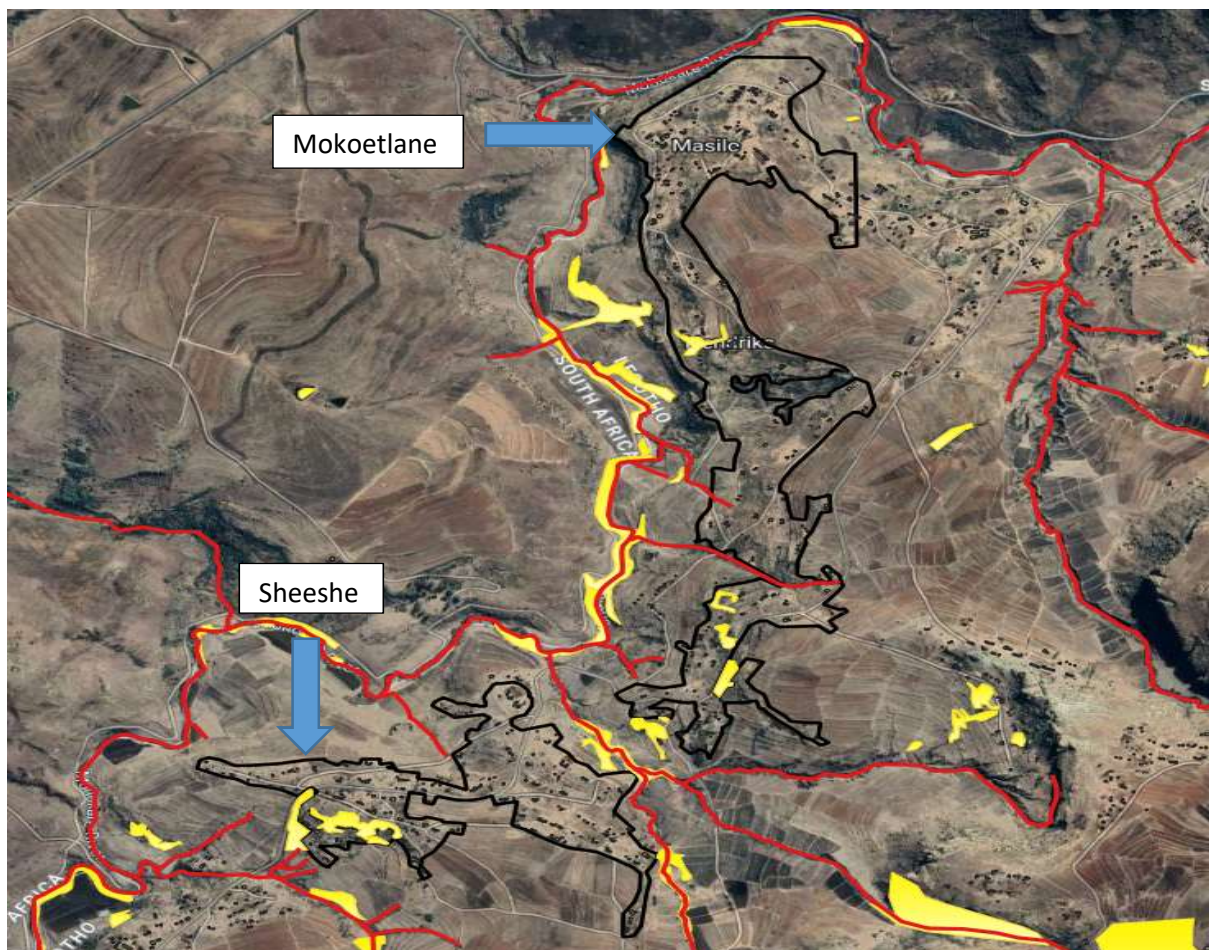


Figure 30: Land cover input layer for villages of Sheeshe and Mokoetlaneng

4.1.3 Road Maps

The other input layers utilized in this study are road maps for all community councils sourced from Google Maps. GISEle software which computes routing is most importantly programmed

in such a way that the reticulation of both Medium Voltage (MV) and Low Voltage (LV) lines follow the road route to answer one of the problem statements of difficulty in attending to maintenance due to terrain and lines that are constructed away from roads. The satellite captured bigger size roads and ignored the footpaths as this will mislead the program into thinking that the vehicles can have access whereas only people can access such roads. All the layers are incorporated and used by GISEle after weighing all the other input road layer files.

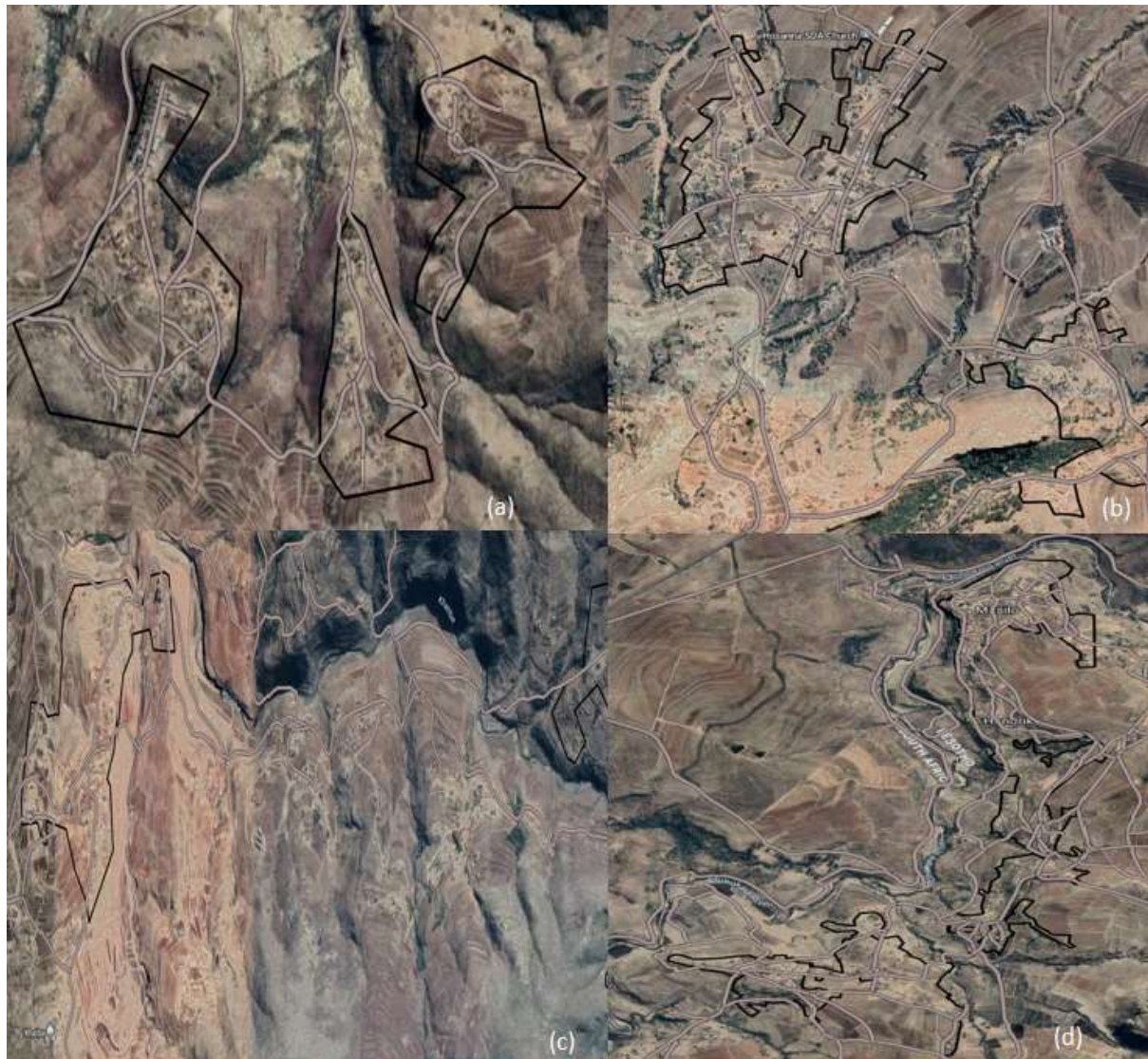


Figure 31: Roads input layers for (a) Makhunoana 1, (b) Ts'a-le-Moleka, (c) Makhunoana 2 and (d) Ntelle community councils

4.1.4 Electrical Network Shapefile

Electrical shapefile layers collected from Lesotho Electricity Company (LEC) as the utility responsible for the execution of network extension and monitoring are existing electrical network and substations layers respectively.

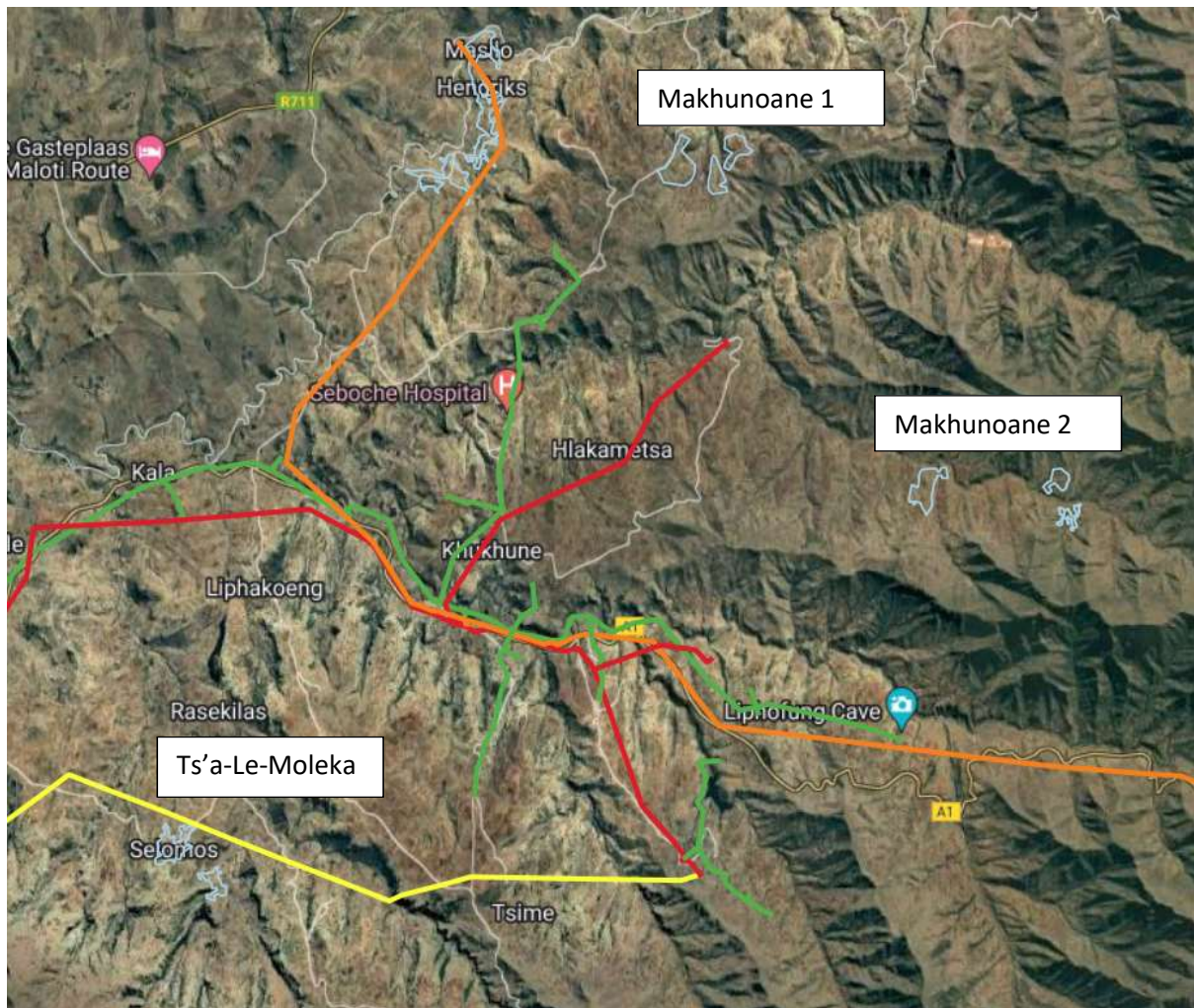


Figure 32: Existing Electrical Network Shapefile

Figure 32 shows the input layers for the existing electrical network which are other important information for the success of this study. From Figure 32, the yellow colour represents the existing 132kV network which is a transmission line dedicated to the supply of main substations and the lines are from the 'Muela hydropower substation to the Maputsoe substation then to the main country substation which also incorporates the National Control Center which is Mabote substation. The orange colour represents the 88kV existing line which is a dedicated supply to the diamond mines and cannot in any way be utilized to electrify the proposed villages. Furthermore, the red colour represents the existing 33kV lines which feed the existing neighbouring substations which can be utilized to feed these community councils as most are step-down transformers from 33kV to 11kV as illustrated in Figure 33. Moreover, the green colour represents the 11kV existing line ideal for the proposed network extensions and lower connection costs.

The last input layer as depicted in Figure 33 represents the existing substations in the Butha Buthe district and near the selected villages. There are about four substations that MILP will utilise to optimize and get a supply from to supply these villages at the minimum costs. GISEle only considers the substations that are near to the proposed network extension or can propose a new source if the demand exceeds the available supply.



Figure 33: Existing Substations of Ngoajane, Khukhune, Hololo, Muela and Buthe-Buthe

4.1.5 Data Processing

All the layers were merged using QGIS software to make one output layer with all the relevant inputs and the produced csv file which is used in a GISEle interface together with the conda python program. The csv input file incorporating all the merged layers is annexed in Appendix 1. The electrical data adopted to perform the analysis are shown in Table 5 [41]. The data was sourced from LEC and is the same as the one that is used in the Electrification MasterPlan [43]. The cost for both MV and LV lines also was sourced from the study that was conducted in 2015 by PWC [43]. The study titled Asset Verification and Valuation was applicable for the next ten years of which the inflation rate was at 10% per annum for all the electrical material and labours cost.

Table 5: Electrical Parameters

Load Per Capita	570 Watts
Number of People per Household	6
Low Voltage Maximum Length	500m
MV line Cost	10000 €/km
LV line Cost	7500 €/km

4.2 Clustering

After the data collection and processing, the step that followed was population clustering and load distribution for all the 10 villages of the selected study area. The regular points grid

created was considered for this process as the MILP algorithm went through the entire target area and found the densely populated one that best suits the electrification. The computation is done based on the csv file that was created which is the product of all the input data from different sources. The environment was also created by python to accommodate the satellite location of the area where the study was conducted, as GISEle does not use a standard IP address for all the locations around the globe but rather creates its environment for a specific study area and in this case the IP address generated for Lesotho that was used in this computation or rather the interface is <http://127.0.0.1:8050/>. The villages are now clustered together to make an electricity network connection to the villages cheaper by comparing the density and putting them together where it is necessary to allow for the proper calculation of the power demand in the routing stage.

GISEle used DBSCAN as the clustering algorithm as mentioned in previous chapters. Filho, V et al performed sensitivity analysis to define the two parameters which are the radius of the neighbourhood (eps) and minimum population (MinPts) [15]. The objective was to increase the percentage of clustered people and reduce the total clustered area with the clusters merging possibility if the distance is too small. The results of the cluster analysis are shown in Figure 34 where there is a total number of 10 clusters with 2640 as the total number of households for four community councils.



Figure 34: Population clustering for (a) Makhunoana 1, (b) Ts'a-le-moleka, (c) Makhunoana 2 and (d) Ntelle community councils

4.3 Routing

Figure 35 represents the grid routing for Makhunoana 1 Community Council where the red triangle points are classified as outputs notes in GISEle and sometimes are called the Medium Voltage to Low Voltage substations. In our common term, they are called the 11kV Stepdown transformers and they are of different sizes influenced by the demand of each cluster. The bigger the population cluster the more demand of supply which translates to a bigger transformer size or more transformers depending on the size of the village as each transformer Low voltage network only covers the radius of 500m distance from the transformer as explained in the previous section in the input parameters section. GISEle calculates the power that is needed by each cluster as it is shown by white text on each transformer. The blue line represents the Low Voltage network and it cuts across the village which makes it easy for everyone to tap from the LV line and connect to the households. The yellow line is the Medium-voltage grid inside each cluster whereas the green line is the Medium Voltage grid which connects all the transformers to the substation. Makhunoana 1 Community Council comprises 4 transformers with different power demands. Three output nodes demand are 42.348kW, 41.109kW and 34.86kW respectively. This translates to 50kVA rated transformers which are available in the market whereas the other output node of 50.954kW will be covered by a 100kVA transformer respectively.



Figure 35: Routing for Makhunoana 1 Community Council

Figure 36 represents the grid routing for Ts'a-le-moleka Community Council which comprises 3 shared power demands which are 113.204kW, 42.874kW and 68.974kW. For 113.204kW demand, the 200kVA transformer is selected.

The current will be distributed across the Ts'a-le-Moleka Community Council and will cater for the future demand of that council should there be any population increase or more power demand. The Low Voltage network is depicted in blue lines of which there will still be a need for connection to the households whereas the green line represents the 11kV network from the close connection point.

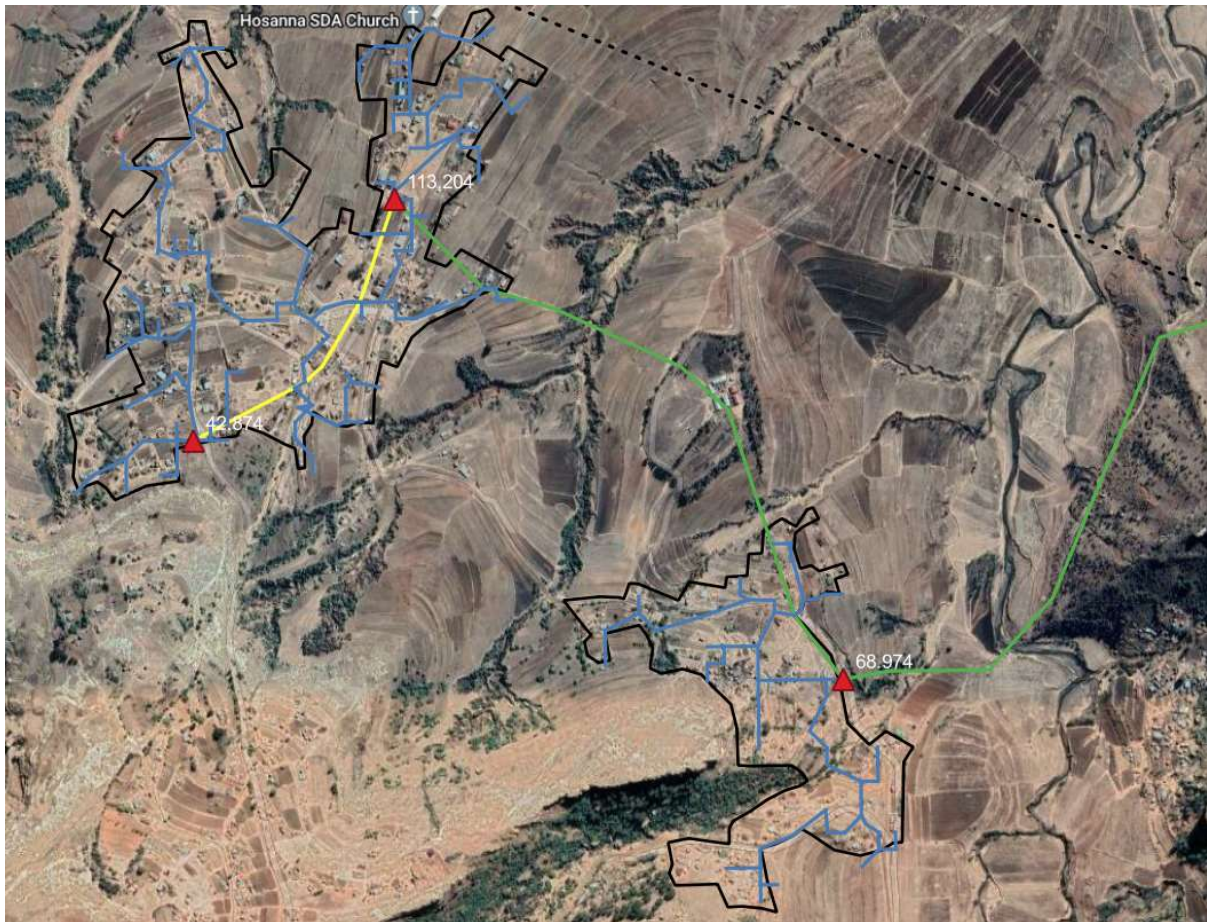


Figure 36: Routing for Ts'a-le-moleka Community Council

Figure 37 represents Makhunoana 2 Community Council which comprise 4 power demands shared amongst the clusters which are 32.334kW, 42.348kW, 34.86kW and 25.932kW. The output nodes which in this case represent the power demand will all be fed by a 50kVA transformer for each node to meet the demand for the Makhunoana 2 Community Council. The green line is the proposed 11kV line which is fed from the closer substation while the blue line represents the 400V Low Voltage network distributed around the villages.

Lastly, the Ntelle Community Council comprise 6 output nodes with different power demand for each cluster and they are 38.62kW, 52.174kW, 34.86, 28.501kW, 99.231kW and 48.507kW. For the output node with 99.231kW demand, the selection of the required transformer will be 200kVA to cater for the future power demand, not 100kVA as this might seem to be the closer rated transformer rating available in the market. The yellow line is the proposed 11kV line that connects the transformer with the routing of the main feeder that

runs far away from those proposed transformers. The blue line and green lines are the Low Voltage network and Medium-Voltage line respectively. The routing process is depicted in Appendix 2 in which the new developed GISEle programme with MILP algorithm is shown before the final development of the new internet interface. The process of the preprogrammed GISEle model is shown in appendix 3 to 5 as the programme is still under development and was done for only this particular study by the developers.



Figure 37: Routing for Makhunoana 2 Community Council

The results are summarised in Table 6. where the cost of each cluster with the length of the grid is stipulated. Makhunoana 1 total electrification cost which comprises 4 clusters sums up to €74, 303 and translates to M1, 117, 517.12. Ts'a-le-moleka comprises 3 clusters which sum up to €92, 103 and translate to M1, 385, 229.12. Moreover, Makhunoana 2 community council which comprises 4 clusters and total electrification cost sums up to €73, 653 which is equivalent to M1, 107, 741.12. Lastly, the Ntelle community council comprises 6 clusters and the total electrification cost is €133, 274 which is equivalent to M2, 004, 440.96. The electrification cost for Makhunoana 1, Ts'a-Le_Moleka, and Ntelle community councils are cheaper with GISEle as compared to EMP as illustrated in Table 7. The costs of community council of Makhunoane 2 is slightly higher with GISEle compared to EMP. The average cost of this community council proves GISEle to be more viable as it also design the entire network.

Table 6: Electrical Routing final resume

Cluster	Sub_cluster	Population	Load [kW]	Transformer_rated_power [kVA]	Cost[euro]	Grid_Length [km]	Grid Cost [euro]
1	0	161	50.95374	100	2100	2.043	25112
2	0	105	34.86012	50	1500	1.528	16699
3	0	127	41.10857	50	1500	1.7	19032
3	1	131	42.34844	50	1500	1.18	13460
Sub Total							74303
8	0	389	113.2038	200	2800	4.416	46096
8	1	133	42.87413	50	1500	1.42	17242
9	0	226	68.97357	100	2100	2.351	28765
Sub Total							92103
5	0	105	34.86012	50	1500	1.582	24489
6	0	74	25.93161	50	1500	1.14	12959
7	0	131	42.34844	50	1500	1.52	17831
7	1	96	32.334	50	1500	1.663	18374
Sub Total							73653
4	0	153	48.50709	100	2100	1.495	16751
4	1	337	99.23064	200	2800	3.858	39143
10	0	118	38.61955	50	1500	1.629	17328
10	1	166	52.17386	100	2100	2.424	25623
10	2	105	34.86012	50	1500	1.931	17546
10	3	83	28.5094	50	1500	1.579	16883
Sub Total							133274

Table 7: Electrification costs of EMP vs GISEle

Priority	EA Code	Community Council	EMP	GISEle
8	1010123024	Makhunoane 1	2, 475, 000	1, 117, 517. 12
10	1040413033	Ts'a-Le-Moleka	1, 815, 000	1, 385, 229.12
22	1010123043	Makhunoane 2	1, 095, 000	1, 107, 741.12
49	1010123025	Ntelle	2, 070, 000	2, 004, 440.96

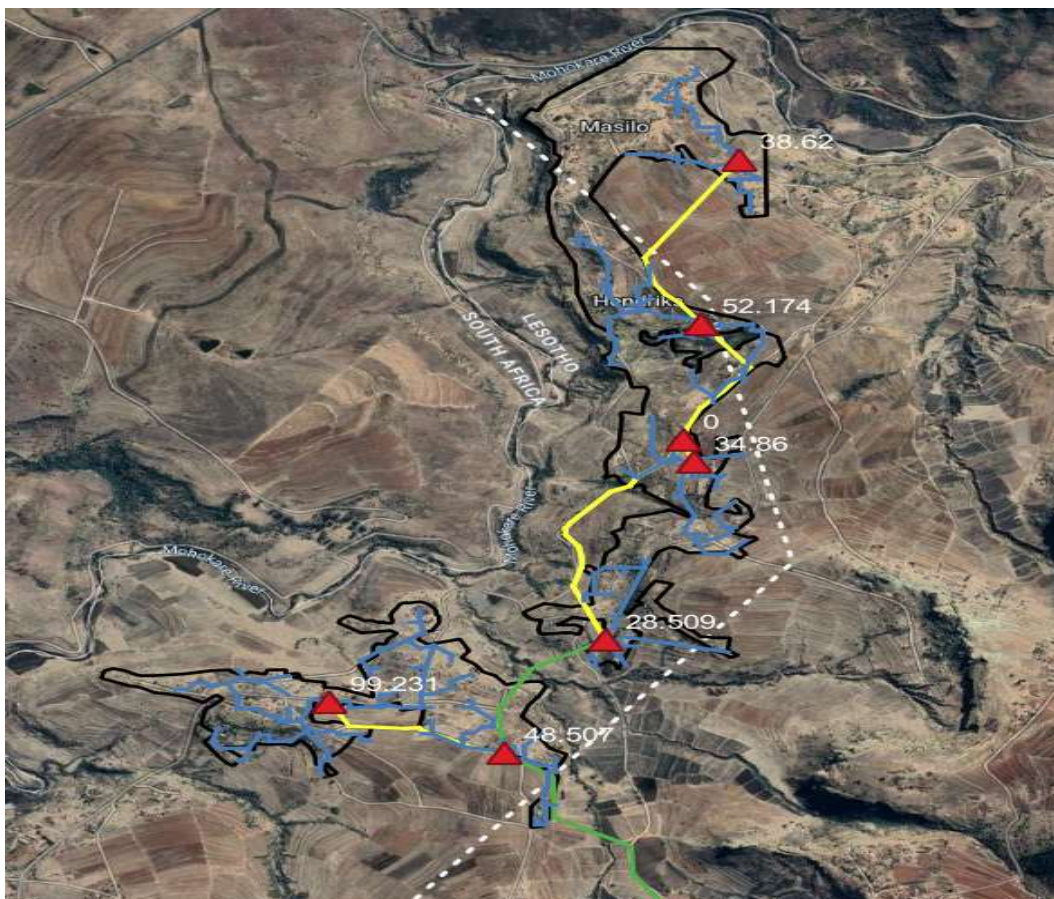


Figure 38: Routing for Ntelle Community Council

Chapter 5: Conclusions and Recommendations

The extension of the grid is an expensive exercise in its nature as it requires a huge amount of capital cost and investment as far as rural electrification is concerned due to un-user friendly environment and other difficult aspects as mentioned in previous chapters. However, to improve the fight and to make grid extension relevant in comparison to other solutions such as microgrids, it is crucial to adopt accurate optimization tools that work best in finding the optimal configuration of the electrical network such as GISEle. Thus process of routing proved to be the most important among all other processes but can not work alone as it is also dependent on other processes

The dissertation aimed to improve the already existing electrification planning done by others and adopt GISEle to replace the already existing planning tools in Lesotho Electricity Company to enhance the grid extension solution. In addition, to discard the already existing electrical constraints on the current version of GISEle to only concentrate on grid extension rather than weighing and comparing the cost to either microgrids or stand-alone systems.

The MILP-based model has been developed to improve the existing graph theory-based approach which was more suitable if all other electrification options were considered. MILP introduced several features such as line size categorization, optimal grid connection and terrain cost consideration. The challenge compared to the graph theory approach is the computational time required as the model was designed to allow for only 1250 km² for cluster coverage. However, the gap was overcome by providing the provision to allow for the use of the heuristic algorithm as it is also a good algorithm that can be integrated with GISEle tool.

The total electrification cost for all the community councils using GISELE as compared to the Electrification Master Plan estimates proved to be cheaper and more effective as all the planning is detailed and costs calculation were made with similar market price for EMP in 2017.

As far as the results seemed to be good, the approach still needs further improvement to work fully and to avoid being dependent on other algorithms such as heuristic to allow GISEle to run independently and to make it a user-friendly programme that can be used by everyone with electrification planning without programming knowledge. The other important aspect like reliability assessment is considered for future study work.

References

- [1] F. Kemausuor, E. Adkins, I. Adu-Poku, A. Brew-Hammond, and V. Modi, "Electrification planning using Network Planner tool: The case of Ghana," *Energy Sustain. Dev.*, vol. 19, pp. 92–101, Apr. 2014, doi: 10.1016/j.esd.2013.12.009.
- [2] IEA, "Achieving modern energy for all by 2030 remains possible despite pandemic-related delays - Analysis report," *IEA*, Jul. 20, 2020.
- [3] P. Cicilio, M. Orosz, A. Mueller, and E. Cotilla-Sanchez, "uGrid: Reliable Minigrid Design and Planning Toolset for Rural Electrification," *IEEE Access*, vol. 7, pp. 163988–163999, 2019, doi: 10.1109/ACCESS.2019.2952896.
- [4] W. Rosa, Ed., "Transforming Our World: The 2030 Agenda for Sustainable Development," in *A New Era in Global Health*, New York, NY: Springer Publishing Company, 2017. doi: 10.1891/9780826190123.ap02.
- [5] E. Loken, "Use of multicriteria decision analysis methods for energy planning problems," *Renew. Sustain. Energy Rev.*, vol. 11, no. 7, pp. 1584–1595, Sep. 2007, doi: 10.1016/j.rser.2005.11.005.
- [6] P. Mulder and J. Tembe, "Rural electrification in an imperfect world: A case study from Mozambique," *Energy Policy*, vol. 36, no. 8, pp. 2785–2794, Aug. 2008, doi: 10.1016/j.enpol.2008.05.018.
- [7] M. Senatla, M. Nchake, B. M. Taele, and I. Hapazari, "Electricity capacity expansion plan for Lesotho – implications on energy policy," *Energy Policy*, vol. 120, pp. 622–634, Sep. 2018, doi: 10.1016/j.enpol.2018.06.003.
- [8] B. M. Taele, K. K. Gopinathan, and L. Mokhuts'oane, "The potential of renewable energy technologies for rural development in Lesotho," *Renew. Energy*, vol. 32, no. 4, pp. 609–622, Apr. 2007, doi: 10.1016/j.renene.2006.02.014.
- [9] A. Korkovelos, B. Khavari, A. Sahlberg, M. Howells, and C. Arderne, "The Role of Open Access Data in Geospatial Electrification Planning and the Achievement of SDG7. An OnSSET-Based Case Study for Malawi," *Energies*, vol. 12, no. 7, p. 1395, Apr. 2019, doi: 10.3390/en12071395.
- [10] A. C. Brent and D. E. Rogers, "Renewable rural electrification: Sustainability assessment of mini-hybrid off-grid technological systems in the African context," *Renew. Energy*, vol. 35, no. 1, pp. 257–265, Jan. 2010, doi: 10.1016/j.renene.2009.03.028.
- [11] P. Bertheau, C. Cader, and P. Blechinger, "Electrification Modelling for Nigeria," *Energy Procedia*, vol. 93, pp. 108–112, Aug. 2016, doi: 10.1016/j.egypro.2016.07.157.
- [12] A. Eberhard, K. Gratwick, E. Morella, and P. Antmann, "Accelerating investments in power in sub-Saharan Africa," *Nat. Energy*, vol. 2, no. 2, p. 17005, Feb. 2017, doi: 10.1038/nenergy.2017.5.
- [13] K. B. Debnath and M. Mourshed, "Forecasting methods in energy planning models," *Renew. Sustain. Energy Rev.*, vol. 88, pp. 297–325, May 2018, doi: 10.1016/j.rser.2018.02.002.
- [14] "NCGIA Menu Map." <http://www.ncgia.ucsb.edu/> (accessed Apr. 05, 2022).
- [15] V. G. T. Filho and M. Merlo, "GIS-BASED STRATEGY FOR DISTRIBUTION GRID PLANNING IN RURAL AREAS," p. 134.
- [16] N. M. E. Ahmed, "GIS-Based Planning of Rural Distribution Grid using MILP Approach," *ISPRS Int. J. Geo-Inf.*, vol. 2, no. 3, pp. 1–79, Oct. 2020.
- [17] S. Corigliano, T. Carnovali, D. Edeme, and M. Merlo, "Holistic geospatial data-based procedure for electric network design and least-cost energy strategy," *Energy Sustain. Dev.*, vol. 58, pp. 1–15, Oct. 2020, doi: 10.1016/j.esd.2020.06.008.
- [18] "Ahmed - GIS-Based Planning of Rural Distribution Grid usin.pdf."
- [19] P. Vilaça, A. Street, and J. M. Colmenar, "A MILP-based heuristic algorithm for transmission expansion planning problems," *Electr. Power Syst. Res.*, vol. 208, p. 107882, Jul. 2022, doi: 10.1016/j.epsr.2022.107882.

- [20] J. Shu, L. Wu, Z. Li, M. Shahidehpour, L. Zhang, and B. Han, "A New Method for Spatial Power Network Planning in Complicated Environments," *IEEE Trans. Power Syst.*, vol. 27, no. 1, pp. 381–389, Feb. 2012, doi: 10.1109/TPWRS.2011.2161351.
- [21] A. Samui, S. R. Samantaray, and G. Panda, "Distribution system planning considering reliable feeder routing," *IET Gener. Transm. Distrib.*, vol. 6, no. 6, p. 503, 2012, doi: 10.1049/iet-gtd.2011.0682.
- [22] J. van Bemmelen, W. Quak, M. van Hekken, P. van Oosterom, and P. O. Box, "Vector vs. Raster-based Algorithms for Cross Country Movement Planning," p. 14.
- [23] R. C. Lotero and J. Contreras, "Distribution System Planning With Reliability," *IEEE Trans. Power Deliv.*, vol. 26, no. 4, pp. 2552–2562, 2011, doi: 10.1109/TPWRD.2011.2167990.
- [24] A. B. Kahng and G. Robins, "A new class of iterative Steiner tree heuristics with good performance," *IEEE Trans. Comput.-Aided Des. Integr. Circuits Syst.*, vol. 11, no. 7, pp. 893–902, Jul. 1992, doi: 10.1109/43.144853.
- [25] M. R. Ganjavi, "Coordinated comprehensive design of distribution systems at medium and low voltage levels," in *16th International Conference and Exhibition on Electricity Distribution (CIRED 2001)*, Amsterdam, Netherlands, 2001, vol. 2001, pp. v5-29-v5-29. doi: 10.1049/cp:20010893.
- [26] M. Moner-Girona, D. Puig, Y. Mulugetta, I. Kougias, J. AbdulRahman, and S. Szabó, "Next generation interactive tool as a backbone for universal access to electricity," *Wiley Interdiscip. Rev. Energy Environ.*, vol. 7, no. 6, p. e305, Nov. 2018, doi: 10.1002/wene.305.
- [27] D. Ellman and A. B. Physics, "The Reference Electrification Model: A Computer Model for Planning Rural Electricity Access," p. 109.
- [28] C. Mateo Domingo, T. Gomez San Roman, A. Sanchez-Mirallès, J. P. Peco Gonzalez, and A. Candela Martinez, "A Reference Network Model for Large-Scale Distribution Planning With Automatic Street Map Generation," *IEEE Trans. Power Syst.*, vol. 26, no. 1, pp. 190–197, Feb. 2011, doi: 10.1109/TPWRS.2010.2052077.
- [29] B. Khavari and A. Sahlberg, "Geo-spatial electricity demand assessment & hybrid off-grid solutions to support electrification efforts using OnSSET: the case study of Tanzania," p. 67.
- [30] ONSSET, "Open Source Spatial Electrification Tool." <http://www.onsset.org/> (accessed Jun. 20, 2021).
- [31] D. Mentis *et al.*, "Lighting the World: the first application of an open source, spatial electrification tool (OnSSET) on Sub-Saharan Africa," *Environ. Res. Lett.*, vol. 12, no. 8, p. 085003, Aug. 2017, doi: 10.1088/1748-9326/aa7b29.
- [32] B. Resch *et al.*, "GIS-Based Planning and Modeling for Renewable Energy: Challenges and Future Research Avenues," *ISPRS Int. J. Geo-Inf.*, vol. 3, no. 2, pp. 662–692, May 2014, doi: 10.3390/ijgi3020662.
- [33] S. Pfenninger and B. Pickering, "Calliope: a multi-scale energy systems modelling framework," *J. Open Source Softw.*, vol. 3, no. 29, p. 825, Sep. 2018, doi: 10.21105/joss.00825.
- [34] S. Jebaraj and S. Iniyan, "A review of energy models," *Renew. Sustain. Energy Rev.*, vol. 10, no. 4, pp. 281–311, Aug. 2006, doi: 10.1016/j.rser.2004.09.004.
- [35] A. M. Foley, B. P. Ó Gallachóir, J. Hur, R. Baldick, and E. J. McKeogh, "A strategic review of electricity systems models," *Energy*, vol. 35, no. 12, pp. 4522–4530, Dec. 2010, doi: 10.1016/j.energy.2010.03.057.
- [36] S. Corigliano, T. Carnovali, D. Edeme, and M. Merlo, "Holistic geospatial data-based procedure for electric network design and least-cost energy strategy," *Energy Sustain. Dev.*, vol. 58, pp. 1–15, Oct. 2020, doi: 10.1016/j.esd.2020.06.008.
- [37] Q. Ji, S. Barr, P. James, and D. Fairbairn, "A GEOSPATIAL ANALYSIS FRAMEWORK FOR FINE SCALE URBAN INFRASTRUCTURE NETWORKS," *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.*, vol. XLII-4, pp. 291–296, Sep. 2018, doi: 10.5194/isprs-archives-XLII-4-291-2018.

- [38] BOS, "2011 Lesotho Demographic Survey - Analytical Report, Vol. I," *Ministry of Development Planning - Bureau of Statistics (BoS)*. https://energydata.info/about_us (accessed Jun. 20, 2021).
- [39] C. Monteiro, I. J. Ramirez-Rosado, V. Miranda, P. J. Zorzano-Santamaria, E. Garcia-Garrido, and L. A. Fernandez-Jimenez, "GIS Spatial Analysis Applied to Electric Line Routing Optimization," *IEEE Trans. Power Deliv.*, vol. 20, no. 2, pp. 934–942, Apr. 2005, doi: 10.1109/TPWRD.2004.839724.
- [40] D. E. Carnovali, "an innovative GIS-based approach for electric networks routing, Ph.D. thesis, Politecnico di Milano," *Energy Sustain. Dev.*, vol. 58, pp. 1–15, 2019, doi: 10.1016/j.esd.2020.06.008.
- [41] D. Fernandez, "Formulation of the Lesotho electrification master plan - Off-Grid master plan report (Draft)," Jun. 15, 2018.
- [42] WORLDPOP, "Population Density Raster layer." <https://www.worldpop.org> (accessed Apr. 12, 2022).
- [43] LEC, "Asset Verification and Valuation Preliminary Report, pwc," *Assets Management Project*. <https://www.lec.co.ls.org/reports> (accessed Jul. 09, 2015).

Appendix

Appendix 1: Input parameters

	X	Y	Geometry	ID	Population	Elevation (m)	Slope (degrees)	Land_cover (m2)	Road_dist (km)	Weight
0	-142409	3170610	POINT (-142409.2530258508 3170610.478204253)	0	0	1851	12.256307	2	29.960762	2.38643
1	-142379	3170610	POINT (-142379.2530258508 3170610.478204253)	1	0	1851	19.639633	4	11.183633	1.5
2	-142349	3170610	POINT (-142349.2530258508 3170610.478204253)	2	0	1840	19.639633	4	17.516982	2.49299
3	-142439	3170640	POINT (-142439.2530258508 3170640.478204253)	3	0	1852	9.5178375	3	36.008346	2.35935
4	-142409	3170640	POINT (-142409.2530258508 3170640.478204253)	4	0	1864	9.5178375	3	12.849681	1.5
5	-142379	3170640	POINT (-142379.2530258508 3170640.478204253)	5	0	1864	18.680374	3	14.449265	1.5
6	-142349	3170640	POINT (-142349.2530258508 3170640.478204253)	6	0	1855	18.680374	4	8.8525711	1.5
7	-142439	3170670	POINT (-142439.2530258508 3170670.478204253)	7	0	1852	9.5178375	4	26.64344	2.31253
8	-142409	3170670	POINT (-142409.2530258508 3170670.478204253)	8	0	1864	9.5178375	1	18.157807	6.2701
9	-142379	3170670	POINT (-142379.2530258508 3170670.478204253)	9	0	1864	18.680374	4	31.594609	2.54021
10	-142349	3170670	POINT (-142349.2530258508 3170670.478204253)	10	0	1855	18.680374	3	16.282766	2.46365
11	-142319	3170670	POINT (-142319.2530258508 3170670.478204253)	11	0	1833	22.988262	3	18.819785	2.58347
12	-142469	3170700	POINT (-142469.2530258508 3170700.478204253)	12	0	1852	16.728613	4	43.08612	2.5517

13	-142439	3170700	POINT (-142439.2530258508 3170700.478204253)	13	0	1852	6.7030325	4	14.177694	1.5
14	-142409	3170700	POINT (-142409.2530258508 3170700.478204253)	14	0	1864	6.7030325	4	18.590328	2.21612
15	-142379	3170700	POINT (-142379.2530258508 3170700.478204253)	15	0	1864	16.092079	4	25.505319	2.44914
16	-142349	3170700	POINT (-142349.2530258508 3170700.478204253)	16	0	1855	16.092079	3	12.646691	1.5
17	-142319	3170700	POINT (-142319.2530258508 3170700.478204253)	17	0	1841	22.873804	3	26.633838	2.61959
18	-142469	3170730	POINT (-142469.2530258508 3170730.478204253)	18	0	1852	16.728613	4	31.055013	2.49155
19	-142439	3170730	POINT (-142439.2530258508 3170730.478204253)	19	0	1852	6.7030325	3	2.226052	1.5
20	-142409	3170730	POINT (-142409.2530258508 3170730.478204253)	20	0	1864	6.7030325	4	29.077428	2.26856
21	-142379	3170730	POINT (-142379.2530258508 3170730.478204253)	21	4.3477079	1864	16.092079	4	14.756075	1.5
22	-142349	3170730	POINT (-142349.2530258508 3170730.478204253)	22	0	1855	16.092079	3	20.364808	2.42344
23	-142319	3170730	POINT (-142319.2530258508 3170730.478204253)	23	0	1841	22.873804	3	41.599094	2.69442
24	-142499	3170760	POINT (-142499.2530258508 3170760.478204253)	24	0	1841	16.728613	3	65.170843	2.66213
25	-142469	3170760	POINT (-142469.2530258508 3170760.478204253)	25	0	1859	16.728613	4	36.586309	2.51921
26	-142439	3170760	POINT (-142439.2530258508 3170760.478204253)	26	4.3477079	1859	6.7030325	1	15.161704	6.19898
27	-142409	3170760	POINT (-142409.2530258508 3170760.478204253)	27	0	1866	6.7030325	4	30.35122	2.27493
28	-142379	3170760	POINT (-142379.2530258508 3170760.478204253)	28	0	1866	16.092079	4	24.074077	2.44199

29	-142349	3170760	POINT (-142349.2530258508 3170760.478204253)	29	0	1858	16.092079	4	27.866554	2.46095
30	-142319	3170760	POINT (-142319.2530258508 3170760.478204253)	30	0	1841	22.873804	3	52.6643	2.74974
31	-142499	3170790	POINT (-142499.2530258508 3170790.478204253)	31	0	1841	16.7927	3	50.79913	2.59175
32	-142469	3170790	POINT (-142469.2530258508 3170790.478204253)	32	0	1859	16.7927	4	24.972392	2.46262
33	-142439	3170790	POINT (-142439.2530258508 3170790.478204253)	33	0	1859	11.801414	1	15.634372	6.30509
34	-142409	3170790	POINT (-142409.2530258508 3170790.478204253)	34	0	1866	11.801414	4	30.590078	2.37987
35	-142379	3170790	POINT (-142379.2530258508 3170790.478204253)	35	0	1866	17.657776	4	5.9347414	1.5
36	-142349	3170790	POINT (-142349.2530258508 3170790.478204253)	36	0	1858	17.657776	4	24.08542	2.47839
37	-142319	3170790	POINT (-142319.2530258508 3170790.478204253)	37	0	1841	24.200275	4	54.083212	2.7914
38	-142499	3170820	POINT (-142499.2530258508 3170820.478204253)	38	0	1851	16.7927	3	35.099421	2.51326
39	-142469	3170820	POINT (-142469.2530258508 3170820.478204253)	39	0	1867	16.7927	3	21.484413	2.44518
40	-142439	3170820	POINT (-142439.2530258508 3170820.478204253)	40	0	1867	11.801414	3	17.454191	2.31419
41	-142409	3170820	POINT (-142409.2530258508 3170820.478204253)	41	0	1873	11.801414	2	25.803965	2.35593
42	-142379	3170820	POINT (-142379.2530258508 3170820.478204253)	42	0	1873	17.657776	2	5.6591963	1.5
43	-142349	3170820	POINT (-142349.2530258508 3170820.478204253)	43	0	1869	17.657776	3	28.322368	2.49958
44	-142319	3170820	POINT (-142319.2530258508 3170820.478204253)	44	0	1854	24.200275	4	57.586149	2.80892

45	-142529	3170850	POINT (-142529.2530258508 3170850.478204253)	45	0	1839	20.00753	4	53.64945	2.68265
46	-142499	3170850	POINT (-142499.2530258508 3170850.478204253)	46	0	1857	16.698092	3	26.330303	2.46722
47	-142469	3170850	POINT (-142469.2530258508 3170850.478204253)	47	0	1874	16.698092	3	7.4390381	1.5
48	-142439	3170850	POINT (-142439.2530258508 3170850.478204253)	48	0	1874	8.0053349	3	34.891169	2.32326
49	-142409	3170850	POINT (-142409.2530258508 3170850.478204253)	49	0	1888	8.0053349	2	12.204905	1.5
50	-142379	3170850	POINT (-142379.2530258508 3170850.478204253)	50	0	1888	13.767156	2	18.704886	2.36295
51	-142349	3170850	POINT (-142349.2530258508 3170850.478204253)	51	0	1882	13.767156	3	43.444151	2.48665
52	-142319	3170850	POINT (-142319.2530258508 3170850.478204253)	52	0	1867	22.944723	4	68.905001	2.83278
53	-142529	3170880	POINT (-142529.2530258508 3170880.478204253)	53	0	1839	20.00753	4	26.23141	2.54556
54	-142499	3170880	POINT (-142499.2530258508 3170880.478204253)	54	0	1857	16.698092	4	26.20434	2.46659
55	-142469	3170880	POINT (-142469.2530258508 3170880.478204253)	55	0	1874	16.698092	4	36.285739	2.517
56	-142439	3170880	POINT (-142439.2530258508 3170880.478204253)	56	0	1874	8.0053349	4	31.268239	2.30515
57	-142409	3170880	POINT (-142409.2530258508 3170880.478204253)	57	0	1888	8.0053349	4	7.9434655	1.5
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59	-142349	3170880	POINT (-142349.2530258508 3170880.478204253)	59	0	1882	13.767156	3	58.896563	2.56391
60	-142319	3170880	POINT (-142319.2530258508 3170880.478204253)	60	0	1867	22.944723	4	85.262642	2.91456

61	-142559	3170910	POINT (-142559.2530258508 3170910.478204253)	61	0	1853	11.188133	3	45.818443	2.44304
62	-142529	3170910	POINT (-142529.2530258508 3170910.478204253)	62	0	1853	20.110996	4	17.260077	2.50324
63	-142499	3170910	POINT (-142499.2530258508 3170910.478204253)	63	0	1867	19.093964	3	17.218908	2.47828
64	-142469	3170910	POINT (-142469.2530258508 3170910.478204253)	64	0	1887	19.093964	4	45.771949	2.62104
65	-142439	3170910	POINT (-142439.2530258508 3170910.478204253)	65	0	1887	10.475793	4	24.993361	2.32402
66	-142409	3170910	POINT (-142409.2530258508 3170910.478204253)	66	0	1903	10.475793	4	11.553787	1.5
67	-142379	3170910	POINT (-142379.2530258508 3170910.478204253)	67	0	1903	16.670784	4	35.94027	2.51464
68	-142349	3170910	POINT (-142349.2530258508 3170910.478204253)	68	0	1902	16.670784	3	64.594578	2.65791
69	-142319	3170910	POINT (-142319.2530258508 3170910.478204253)	69	0	1887	27.929726	3	94.09153	3.09299
70	-142559	3170940	POINT (-142559.2530258508 3170940.478204253)	70	0	1853	11.188133	3	26.653286	2.34721
71	-142529	3170940	POINT (-142529.2530258508 3170940.478204253)	71	0	1853	20.110996	3	41.324734	2.62356
72	-142499	3170940	POINT (-142499.2530258508 3170940.478204253)	72	0	1867	19.093964	3	41.307556	2.59872
73	-142469	3170940	POINT (-142469.2530258508 3170940.478204253)	73	0	1887	19.093964	3	49.61186	2.64024
74	-142439	3170940	POINT (-142439.2530258508 3170940.478204253)	74	0	1887	10.475793	4	19.652566	2.29732
75	-142409	3170940	POINT (-142409.2530258508 3170940.478204253)	75	0	1903	10.475793	4	10.540873	1.5
76	-142379	3170940	POINT (-142379.2530258508 3170940.478204253)	76	0	1903	16.670784	4	40.447456	2.53717

77	-142349	3170940	POINT (-142349.2530258508 3170940.478204253)	77	0	1902	16.670784	3	69.937735	2.68462
78	-142319	3170940	POINT (-142319.2530258508 3170940.478204253)	78	0	1887	27.929726	3	98.995498	3.11751
79	-142289	3170940	POINT (-142289.2530258508 3170940.478204253)	79	0	1887	27.847033	4	128.48708	3.26264
80	-142559	3170970	POINT (-142559.2530258508 3170970.478204253)	80	0	1857	18.020458	3	4.2433333	1.5
81	-142529	3170970	POINT (-142529.2530258508 3170970.478204253)	81	0	1857	22.827066	3	32.640203	2.64842
82	-142499	3170970	POINT (-142499.2530258508 3170970.478204253)	82	0	1875	19.22135	4	62.552057	2.70802
83	-142469	3170970	POINT (-142469.2530258508 3170970.478204253)	83	0	1900	19.22135	4	49.098122	2.64075
84	-142439	3170970	POINT (-142439.2530258508 3170970.478204253)	84	0	1900	6.8452091	4	19.119467	2.22154
85	-142409	3170970	POINT (-142409.2530258508 3170970.478204253)	85	0	1910	6.8452091	4	10.976448	1.5
86	-142379	3170970	POINT (-142379.2530258508 3170970.478204253)	86	0	1910	10.733557	4	40.931782	2.40908
87	-142349	3170970	POINT (-142349.2530258508 3170970.478204253)	87	0	1907	10.733557	1	70.924884	6.55904
88	-142319	3170970	POINT (-142319.2530258508 3170970.478204253)	88	0	1891	24.949402	3	100.92209	3.04547
89	-142289	3170970	POINT (-142289.2530258508 3170970.478204253)	89	0	1891	26.226238	3	130.92057	3.22993
90	-142589	3171000	POINT (-142589.2530258508 3171000.478204253)	90	0	1846	18.460882	3	11.223338	1.5
91	-142559	3171000	POINT (-142559.2530258508 3171000.478204253)	91	0	1857	18.460882	3	19.806726	2.47603
92	-142529	3171000	POINT (-142529.2530258508 3171000.478204253)	92	4.3477079	1857	20.601263	3	46.615353	2.6621

93	-142499	3171000	POINT (-142499.2530258508 3171000.478204253)	93	0	1875	14.693736	4	59.620445	2.58808
94	-142469	3171000	POINT (-142469.2530258508 3171000.478204253)	94	0	1900	14.693736	4	38.98825	2.48492
95	-142439	3171000	POINT (-142439.2530258508 3171000.478204253)	95	0	1900	3.0032492	4	14.343057	1.5
96	-142409	3171000	POINT (-142409.2530258508 3171000.478204253)	96	0	1910	3.0032492	3	24.9072	2.17796
97	-142379	3171000	POINT (-142379.2530258508 3171000.478204253)	97	0	1910	10.22051	4	50.060855	2.44406
98	-142349	3171000	POINT (-142349.2530258508 3171000.478204253)	98	4.3477079	1907	10.22051	1	76.557283	6.57655
99	-142319	3171000	POINT (-142319.2530258508 3171000.478204253)	99	0	1891	21.951157	3	102.29259	2.97431
100	-142289	3171000	POINT (-142289.2530258508 3171000.478204253)	100	0	1891	22.794628	3	119.12244	3.08
101	-142589	3171030	POINT (-142589.2530258508 3171030.478204253)	101	0	1857	18.460882	3	13.399172	1.5
102	-142559	3171030	POINT (-142559.2530258508 3171030.478204253)	102	0	1868	18.460882	3	32.624959	2.54012
103	-142529	3171030	POINT (-142529.2530258508 3171030.478204253)	103	4.3477079	1868	20.601263	3	55.952936	2.70879
104	-142499	3171030	POINT (-142499.2530258508 3171030.478204253)	104	0	1888	14.693736	3	49.079795	2.53537
105	-142469	3171030	POINT (-142469.2530258508 3171030.478204253)	105	0	1901	14.693736	4	19.347158	2.38671
106	-142439	3171030	POINT (-142439.2530258508 3171030.478204253)	106	0	1901	3.0032492	4	11.82365	1.5
107	-142409	3171030	POINT (-142409.2530258508 3171030.478204253)	107	0	1910	3.0032492	4	28.455416	2.1957
108	-142379	3171030	POINT (-142379.2530258508 3171030.478204253)	108	0	1910	10.22051	4	47.79059	2.43271

109	-142349	3171030	POINT (-142349.2530258508 3171030.478204253)	109	4.3477079	1907	10.22051	4	62.064254	2.50408
110	-142319	3171030	POINT (-142319.2530258508 3171030.478204253)	110	0	1891	21.951157	3	76.913799	2.84742
111	-142289	3171030	POINT (-142289.2530258508 3171030.478204253)	111	0	1891	22.794628	3	96.581295	2.96729
112	-142619	3171060	POINT (-142619.2530258508 3171060.478204253)	112	0	1866	14.278161	3	20.353058	2.38248
113	-142589	3171060	POINT (-142589.2530258508 3171060.478204253)	113	0	1866	16.90601	3	32.077571	2.50078
114	-142559	3171060	POINT (-142559.2530258508 3171060.478204253)	114	4.3477079	1875	16.90601	3	52.262118	2.6017
115	-142529	3171060	POINT (-142529.2530258508 3171060.478204253)	115	4.3477079	1875	19.15642	4	68.114974	2.73427
116	-142499	3171060	POINT (-142499.2530258508 3171060.478204253)	116	0	1889	13.153848	3	44.074613	2.47638
117	-142469	3171060	POINT (-142469.2530258508 3171060.478204253)	117	0	1907	13.153848	4	19.071823	2.35137
118	-142439	3171060	POINT (-142439.2530258508 3171060.478204253)	118	0	1907	3.9969707	4	24.184652	2.19264
119	-142409	3171060	POINT (-142409.2530258508 3171060.478204253)	119	0	1911	3.9969707	4	18.367373	2.16355
120	-142379	3171060	POINT (-142379.2530258508 3171060.478204253)	120	4.3477079	1911	9.4991884	4	21.811782	2.28799
121	-142349	3171060	POINT (-142349.2530258508 3171060.478204253)	121	4.3477079	1907	9.4991884	4	35.232224	2.35509
122	-142319	3171060	POINT (-142319.2530258508 3171060.478204253)	122	4.3477079	1896	19.621885	3	54.249669	2.67623
123	-142289	3171060	POINT (-142289.2530258508 3171060.478204253)	123	0	1896	21.072104	3	77.00886	2.82578
124	-142259	3171060	POINT (-142259.2530258508 3171060.478204253)	124	0	1872	21.072104	3	102.72616	2.95436

125	-142619	3171090	POINT (-142619.2530258508 3171090.478204253)	125	4.3477079	1866	14.278161	3	48.530701	2.52337
126	-142589	3171090	POINT (-142589.2530258508 3171090.478204253)	126	4.3477079	1866	16.90601	4	59.229394	2.63653
127	-142559	3171090	POINT (-142559.2530258508 3171090.478204253)	127	0	1875	16.90601	4	48.83572	2.58457
128	-142529	3171090	POINT (-142529.2530258508 3171090.478204253)	128	0	1875	19.15642	3	44.786721	2.61762
129	-142499	3171090	POINT (-142499.2530258508 3171090.478204253)	129	0	1889	13.153848	2	25.96765	2.38585
130	-142469	3171090	POINT (-142469.2530258508 3171090.478204253)	130	0	1907	13.153848	2	2.3185291	1.5
131	-142439	3171090	POINT (-142439.2530258508 3171090.478204253)	131	0	1907	3.9969707	4	23.742143	2.19043
132	-142409	3171090	POINT (-142409.2530258508 3171090.478204253)	132	0	1911	3.9969707	4	19.704387	2.17024
133	-142379	3171090	POINT (-142379.2530258508 3171090.478204253)	133	0	1911	9.4991884	4	10.130555	1.5
134	-142349	3171090	POINT (-142349.2530258508 3171090.478204253)	134	0	1907	9.4991884	4	12.574045	1.5
135	-142319	3171090	POINT (-142319.2530258508 3171090.478204253)	135	0	1896	19.621885	4	36.507678	2.58752
136	-142289	3171090	POINT (-142289.2530258508 3171090.478204253)	136	0	1896	21.072104	3	62.120413	2.75133
137	-142259	3171090	POINT (-142259.2530258508 3171090.478204253)	137	0	1872	21.072104	4	90.471437	2.89309
138	-142649	3171120	POINT (-142649.2530258508 3171120.478204253)	138	0	1871	16.622585	4	55.313668	2.61039
139	-142619	3171120	POINT (-142619.2530258508 3171120.478204253)	139	4.3477079	1874	16.622585	4	40.836884	2.53801
140	-142589	3171120	POINT (-142589.2530258508 3171120.478204253)	140	4.3477079	1874	18.912428	2	29.248118	2.53405

141	-142559	3171120	POINT (-142559.2530258508 3171120.478204253)	141	0	1886	18.912428	2	22.908617	2.50235
142	-142529	3171120	POINT (-142529.2530258508 3171120.478204253)	142	0	1886	18.541433	2	14.828006	1.5
143	-142499	3171120	POINT (-142499.2530258508 3171120.478204253)	143	0	1900	11.609874	1	12.075723	1.5
144	-142469	3171120	POINT (-142469.2530258508 3171120.478204253)	144	0	1916	11.609874	1	17.578057	6.31074
145	-142439	3171120	POINT (-142439.2530258508 3171120.478204253)	145	0	1916	6.0369844	2	40.40614	2.31231
146	-142409	3171120	POINT (-142409.2530258508 3171120.478204253)	146	0	1915	6.0369844	4	22.728786	2.22392
147	-142379	3171120	POINT (-142379.2530258508 3171120.478204253)	147	4.3477079	1915	10.19556	4	13.051754	1.5
148	-142349	3171120	POINT (-142349.2530258508 3171120.478204253)	148	160.86519	1910	10.19556	4	6.2523202	1.5
149	-142319	3171120	POINT (-142319.2530258508 3171120.478204253)	149	0	1900	17.765244	4	27.66273	2.49881
150	-142289	3171120	POINT (-142289.2530258508 3171120.478204253)	150	0	1900	20.122162	3	56.469499	2.69956
151	-142259	3171120	POINT (-142259.2530258508 3171120.478204253)	151	0	1880	20.122162	3	82.275045	2.82859
152	-142649	3171150	POINT (-142649.2530258508 3171150.478204253)	152	0	1871	16.622585	4	34.907676	2.50836
153	-142619	3171150	POINT (-142619.2530258508 3171150.478204253)	153	4.3477079	1874	16.622585	2	12.935714	1.5
154	-142589	3171150	POINT (-142589.2530258508 3171150.478204253)	154	4.3477079	1874	18.912428	2	1.6684374	1.5
155	-142559	3171150	POINT (-142559.2530258508 3171150.478204253)	155	0	1886	18.912428	2	8.0347158	1.5
156	-142529	3171150	POINT (-142529.2530258508 3171150.478204253)	156	0	1886	18.541433	2	15.293435	2.45538

157	-142499	3171150	POINT (-142499.2530258508 3171150.478204253)	157	0	1900	11.609874	1	19.449013	6.32009
158	-142469	3171150	POINT (-142469.2530258508 3171150.478204253)	158	0	1916	11.609874	1	39.495779	6.42033
159	-142439	3171150	POINT (-142439.2530258508 3171150.478204253)	159	0	1916	6.0369844	4	46.305758	2.34181
160	-142409	3171150	POINT (-142409.2530258508 3171150.478204253)	160	0	1915	6.0369844	4	20.396935	2.21227
161	-142379	3171150	POINT (-142379.2530258508 3171150.478204253)	161	4.3477079	1915	10.19556	4	16.935658	2.27792
162	-142349	3171150	POINT (-142349.2530258508 3171150.478204253)	162	0	1910	10.19556	4	15.985764	2.27317
163	-142319	3171150	POINT (-142319.2530258508 3171150.478204253)	163	4.3477079	1900	17.765244	4	15.359797	2.43729
164	-142289	3171150	POINT (-142289.2530258508 3171150.478204253)	164	0	1900	20.122162	3	44.903253	2.64173
165	-142259	3171150	POINT (-142259.2530258508 3171150.478204253)	165	0	1880	20.122162	3	74.810967	2.79127
166	-142619	3171180	POINT (-142619.2530258508 3171180.478204253)	166	0	1884	21.246082	3	8.0885922	1.5
167	-142589	3171180	POINT (-142589.2530258508 3171180.478204253)	167	0	1884	19.979818	3	29.581473	2.56163
168	-142559	3171180	POINT (-142559.2530258508 3171180.478204253)	168	0	1902	19.979818	3	37.362278	2.60053
169	-142529	3171180	POINT (-142529.2530258508 3171180.478204253)	169	0	1902	14.100423	3	45.253824	2.50305
170	-142499	3171180	POINT (-142499.2530258508 3171180.478204253)	170	0	1910	8.4336033	1	47.558572	6.39515
171	-142469	3171180	POINT (-142469.2530258508 3171180.478204253)	171	0	1918	8.4336033	4	59.276618	2.45375
172	-142439	3171180	POINT (-142439.2530258508 3171180.478204253)	172	0	1918	5.5021634	4	34.31666	2.27162

173	-142409	3171180	POINT (-142409.2530258508 3171180.478204253)	173	0	1921	5.5021634	4	11.432754	1.5
174	-142379	3171180	POINT (-142379.2530258508 3171180.478204253)	174	4.3477079	1921	11.188133	4	20.892382	2.31841
175	-142349	3171180	POINT (-142349.2530258508 3171180.478204253)	175	0	1916	11.188133	4	29.71603	2.36253
176	-142319	3171180	POINT (-142319.2530258508 3171180.478204253)	176	4.3477079	1903	15.843113	4	18.041022	2.40613
177	-142289	3171180	POINT (-142289.2530258508 3171180.478204253)	177	0	1903	17.503244	3	34.074344	2.5247
178	-142259	3171180	POINT (-142259.2530258508 3171180.478204253)	178	0	1889	17.503244	3	61.616908	2.66242
179	-142559	3171210	POINT (-142559.2530258508 3171210.478204253)	179	0	1917	15.188033	3	67.150847	2.63683
180	-142529	3171210	POINT (-142529.2530258508 3171210.478204253)	180	0	1917	6.717988	3	72.19501	2.48444
181	-142499	3171210	POINT (-142499.2530258508 3171210.478204253)	181	0	1920	5.1058788	1	76.209877	6.47356
182	-142469	3171210	POINT (-142469.2530258508 3171210.478204253)	182	0	1921	5.1058788	4	54.205199	2.36354
183	-142439	3171210	POINT (-142439.2530258508 3171210.478204253)	183	0	1921	2.5319798	4	24.538119	2.16754
184	-142409	3171210	POINT (-142409.2530258508 3171210.478204253)	184	0	1926	2.5319798	4	8.1261903	1.5
185	-142379	3171210	POINT (-142379.2530258508 3171210.478204253)	185	0	1926	10.492572	4	32.147248	2.36014
186	-142349	3171210	POINT (-142349.2530258508 3171210.478204253)	186	0	1920	10.492572	4	33.306953	2.36594
187	-142319	3171210	POINT (-142319.2530258508 3171210.478204253)	187	4.3477079	1908	12.729097	4	12.038921	1.5
188	-142289	3171210	POINT (-142289.2530258508 3171210.478204253)	188	0	1908	10.466458	3	31.313225	2.35542

189	-142259	3171210	POINT (-142259.2530258508 3171210.478204253)	189	0	1900	10.466458	3	48.319309	2.44046
190	-142619	3171240	POINT (-142619.2530258508 3171240.478204253)	190	0	1880	13.347654	3	41.476597	2.46762
191	-142589	3171240	POINT (-142589.2530258508 3171240.478204253)	191	0	1880	15.188033	4	66.437036	2.63326
192	-142559	3171240	POINT (-142559.2530258508 3171240.478204253)	192	0	1917	15.188033	3	92.069464	2.76142
193	-142529	3171240	POINT (-142529.2530258508 3171240.478204253)	193	0	1917	6.717988	3	100.71496	2.62704
194	-142499	3171240	POINT (-142499.2530258508 3171240.478204253)	194	0	1920	5.1058788	4	85.771053	2.52137
195	-142469	3171240	POINT (-142469.2530258508 3171240.478204253)	195	0	1921	5.1058788	4	56.020658	2.37261
196	-142439	3171240	POINT (-142439.2530258508 3171240.478204253)	196	0	1921	2.5319798	4	26.75032	2.1786
197	-142409	3171240	POINT (-142409.2530258508 3171240.478204253)	197	0	1926	2.5319798	4	9.6356138	1.5
198	-142379	3171240	POINT (-142379.2530258508 3171240.478204253)	198	4.3477079	1926	10.492572	4	35.63861	2.37759
199	-142349	3171240	POINT (-142349.2530258508 3171240.478204253)	199	0	1920	10.492572	4	52.238016	2.46059
200	-142319	3171240	POINT (-142319.2530258508 3171240.478204253)	200	0	1908	12.729097	4	42.004675	2.45682
201	-142289	3171240	POINT (-142289.2530258508 3171240.478204253)	201	0	1908	10.466458	4	24.009547	2.31891
202	-142259	3171240	POINT (-142259.2530258508 3171240.478204253)	202	0	1900	10.466458	4	20.908888	2.3034
203	-142649	3171270	POINT (-142649.2530258508 3171270.478204253)	203	0	1872	17.416533	4	31.10559	2.50783
204	-142619	3171270	POINT (-142619.2530258508 3171270.478204253)	204	0	1880	17.416533	4	56.4772	2.63468

205	-142589	3171270	POINT (-142589.2530258508 3171270.478204253)	205	0	1880	13.441239	4	80.859858	2.66658
206	-142559	3171270	POINT (-142559.2530258508 3171270.478204253)	206	0	1917	13.441239	3	107.39004	2.79923
207	-142529	3171270	POINT (-142529.2530258508 3171270.478204253)	207	0	1917	5.5058322	3	117.37321	2.68697
208	-142499	3171270	POINT (-142499.2530258508 3171270.478204253)	208	0	1929	4.9448185	4	87.92044	2.52907
209	-142469	3171270	POINT (-142469.2530258508 3171270.478204253)	209	0	1929	4.9448185	4	58.535316	2.38214
210	-142439	3171270	POINT (-142439.2530258508 3171270.478204253)	210	0	1929	3.0769429	4	30.377009	2.20665
211	-142409	3171270	POINT (-142409.2530258508 3171270.478204253)	211	0	1930	3.0769429	4	14.803452	1.5
212	-142379	3171270	POINT (-142379.2530258508 3171270.478204253)	212	0	1930	10.535317	4	36.270121	2.38164
213	-142349	3171270	POINT (-142349.2530258508 3171270.478204253)	213	0	1924	10.535317	4	64.899161	2.52479
214	-142319	3171270	POINT (-142319.2530258508 3171270.478204253)	214	0	1911	11.238355	4	49.174801	2.46088
215	-142289	3171270	POINT (-142289.2530258508 3171270.478204253)	215	0	1911	6.3584723	4	21.883426	2.2259
216	-142259	3171270	POINT (-142259.2530258508 3171270.478204253)	216	0	1906	6.3584723	4	12.221542	1.5
217	-142649	3171300	POINT (-142649.2530258508 3171300.478204253)	217	0	1872	17.416533	4	55.88763	2.63174
218	-142619	3171300	POINT (-142619.2530258508 3171300.478204253)	218	0	1880	17.416533	4	73.51195	2.71986
219	-142589	3171300	POINT (-142589.2530258508 3171300.478204253)	219	0	1880	13.441239	4	97.388841	2.74922
220	-142559	3171300	POINT (-142559.2530258508 3171300.478204253)	220	0	1917	13.441239	3	122.18588	2.87321

221	-142529	3171300	POINT (-142529.2530258508 3171300.478204253)	221	4.3477079	1917	5.5058322	3	117.75992	2.68891
222	-142499	3171300	POINT (-142499.2530258508 3171300.478204253)	222	4.3477079	1929	4.9448185	4	88.112304	2.53003
223	-142469	3171300	POINT (-142469.2530258508 3171300.478204253)	223	0	1929	4.9448185	4	58.823104	2.38358
224	-142439	3171300	POINT (-142439.2530258508 3171300.478204253)	224	0	1929	3.0769429	4	30.927933	2.20941
225	-142409	3171300	POINT (-142409.2530258508 3171300.478204253)	225	0	1930	3.0769429	4	15.903348	2.13428
226	-142379	3171300	POINT (-142379.2530258508 3171300.478204253)	226	4.3477079	1930	10.535317	4	36.732764	2.38395
227	-142349	3171300	POINT (-142349.2530258508 3171300.478204253)	227	0	1924	10.535317	4	65.158848	2.52608
228	-142319	3171300	POINT (-142319.2530258508 3171300.478204253)	228	4.3477079	1911	11.238355	4	64.191799	2.53596
229	-142289	3171300	POINT (-142289.2530258508 3171300.478204253)	229	4.3477079	1911	6.3584723	4	40.760091	2.32028
230	-142259	3171300	POINT (-142259.2530258508 3171300.478204253)	230	0	1906	6.3584723	3	20.18052	2.21739
231	-142649	3171330	POINT (-142649.2530258508 3171330.478204253)	231	0	1878	17.416533	4	84.138556	2.77299
232	-142619	3171330	POINT (-142619.2530258508 3171330.478204253)	232	4.3477079	1898	17.416533	3	96.746453	2.83603
233	-142589	3171330	POINT (-142589.2530258508 3171330.478204253)	233	0	1898	13.441239	4	115.93298	2.84194
234	-142559	3171330	POINT (-142559.2530258508 3171330.478204253)	234	0	1927	13.441239	3	139.00013	2.95728
235	-142529	3171330	POINT (-142529.2530258508 3171330.478204253)	235	0	1927	5.5058322	3	125.30432	2.72663
236	-142499	3171330	POINT (-142499.2530258508 3171330.478204253)	236	0	1929	4.9448185	3	97.967098	2.5793

237	-142469	3171330	POINT (-142469.2530258508 3171330.478204253)	237	4.3477079	1929	4.9448185	4	72.759411	2.45326
238	-142439	3171330	POINT (-142439.2530258508 3171330.478204253)	238	0	1929	3.0769429	4	52.823397	2.31888
239	-142409	3171330	POINT (-142409.2530258508 3171330.478204253)	239	0	1930	3.0769429	4	45.680311	2.28317
240	-142379	3171330	POINT (-142379.2530258508 3171330.478204253)	240	0	1930	10.535317	4	56.418705	2.48238
241	-142349	3171330	POINT (-142349.2530258508 3171330.478204253)	241	4.3477079	1924	10.535317	4	77.970826	2.59014
242	-142319	3171330	POINT (-142319.2530258508 3171330.478204253)	242	0	1911	11.238355	4	82.300692	2.62651
243	-142289	3171330	POINT (-142289.2530258508 3171330.478204253)	243	0	1911	8.4406643	4	60.985837	2.46243
244	-142259	3171330	POINT (-142259.2530258508 3171330.478204253)	244	0	1906	8.4406643	4	47.080455	2.39291
245	-142649	3171360	POINT (-142649.2530258508 3171360.478204253)	245	0	1878	17.789463	4	113.21796	2.92716
246	-142619	3171360	POINT (-142619.2530258508 3171360.478204253)	246	0	1898	17.789463	3	122.94611	2.9758
247	-142589	3171360	POINT (-142589.2530258508 3171360.478204253)	247	0	1898	13.763034	4	138.5508	2.96209
248	-142559	3171360	POINT (-142559.2530258508 3171360.478204253)	248	0	1927	13.763034	3	158.35689	3.06112
249	-142529	3171360	POINT (-142529.2530258508 3171360.478204253)	249	4.3477079	1927	8.8467226	3	139.05016	2.86093
250	-142499	3171360	POINT (-142499.2530258508 3171360.478204253)	250	0	1929	8.2549963	3	115.0275	2.72892
251	-142469	3171360	POINT (-142469.2530258508 3171360.478204253)	251	0	1929	8.2549963	4	94.48654	2.62622
252	-142439	3171360	POINT (-142439.2530258508 3171360.478204253)	252	0	1929	8.649663	4	80.150394	2.56246

253	-142409	3171360	POINT (-142409.2530258508 3171360.478204253)	253	4.3477079	1930	8.649663	4	75.633756	2.53987
254	-142379	3171360	POINT (-142379.2530258508 3171360.478204253)	254	0	1930	11.987942	3	82.564185	2.64371
255	-142349	3171360	POINT (-142349.2530258508 3171360.478204253)	255	4.3477079	1924	11.987942	3	98.55569	2.72367
256	-142319	3171360	POINT (-142319.2530258508 3171360.478204253)	256	0	1911	11.207212	4	103.10815	2.72989
257	-142289	3171360	POINT (-142289.2530258508 3171360.478204253)	257	0	1911	8.4406643	4	86.811294	2.59156
258	-142589	3171390	POINT (-142589.2530258508 3171390.478204253)	258	0	1906	13.763034	4	163.56098	3.08714
259	-142559	3171390	POINT (-142559.2530258508 3171390.478204253)	259	4.3477079	1920	13.763034	3	180.64544	3.17256
260	-142529	3171390	POINT (-142529.2530258508 3171390.478204253)	260	0	1920	8.8467226	3	157.38082	2.95258
261	-142499	3171390	POINT (-142499.2530258508 3171390.478204253)	261	0	1937	8.2549963	3	136.62028	2.83689
262	-142469	3171390	POINT (-142469.2530258508 3171390.478204253)	262	0	1939	8.2549963	3	119.83939	2.75298
263	-142439	3171390	POINT (-142439.2530258508 3171390.478204253)	263	0	1939	8.649663	3	108.8938	2.70617
264	-142409	3171390	POINT (-142409.2530258508 3171390.478204253)	264	0	1936	8.649663	3	105.61363	2.68977
265	-142379	3171390	POINT (-142379.2530258508 3171390.478204253)	265	0	1936	11.987942	4	110.68251	2.7843
266	-142349	3171390	POINT (-142349.2530258508 3171390.478204253)	266	0	1928	11.987942	4	123.07314	2.84625
267	-142319	3171390	POINT (-142319.2530258508 3171390.478204253)	267	0	1916	11.207212	4	127.62907	2.85249
268	-142409	3171420	POINT (-142409.2530258508 3171420.478204253)	268	0	1940	9.4929638	3	135.60241	2.85682

269	-142379	3171420	POINT (-142379.2530258508 3171420.478204253)	269	0	1940	10.856344	3	139.58651	2.90492
270	-142349	3171420	POINT (-142349.2530258508 3171420.478204253)	270	0	1933	10.856344	3	149.60205	2.955

Appendix 2: Input parameters

```
1  import ...
12
13  ##### INPUT PARAMETERS #####
14
15  case_study = 'Thung M'
16  resolution = 180 # [meters]
17  roads_weight = 0.5 # relative weight to make lines follow roads. Decrease it to make feeders better follow the roads [0.0-0.4]
18  load_capite = 0.57 # [kW/person]
19  pop_per_household = 6 # Number of people for each house
20  LV_distance = 500 # Maximum length of LV feeders [meters]
21  line_LV_cost = 7500 # Cost of low voltage feeders [€/km]
22
23  # parameters for the MV cable that is used
24  # generic cable
25  # resistance = 0.42 # [ohm/km]
26  # reactance = 0.15 # [ohm/km]
27  # Pmax = 11 # [MVA]
28
29  # cable of 45mm2
30  resistance = 0.594 # [ohm/km]
31  reactance = 0.372 # [ohm/km]
32  Pmax = 4 # [MVA]
33
34  # cable of 70 mm2
35  # resistance = 0.413 # [ohm/km]
36  # reactance = 0.36 # [ohm/km]
37  # Pmax = 5.5 # [MVA]
38
39  line_cost = 10000 # Cost of MV voltage feeders [€/km]
40  voltage = 11 # [kV]
41
42  connection_points = '/con_point.shp'
43
44
```

Appendix 3: Script data processing

```
#####STARTING THE SCRIPT#####

gisele_folder=os.getcwd()
villages_file = 'Villages_areas.geojson'
local_database = True
country_ = 'Lesotho'
# final_clug=13
crs = 22287
resolution_population = 30 # this should be automatic from the raster
coe = 150 # €/MWh of electrical energy supplied
landcover_option='ESNCCI'
if local_database == False:
    database_ = r'C:\Users\silvi\OneDrive - Politecnico di Milano\Documents\2020-2021\Gisele shared\3.Case_Study'
    cluster_folder = r'C:\Users\silvi\OneDrive - Politecnico di Milano\Documents\2020-2021\Gisele shared\3.Case_Study\Lesotho\Villages_areas_48.geojson'
    substations_folder = r'C:\Users\silvi\OneDrive - Politecnico di Milano\Documents\2020-2021\Gisele shared\3.Case_Study\Lesotho\con point.shp'
else:
    database = gisele_folder + '/Database'
    cluster_folder = database + '/' + country_ + '/' + villages_file
    substations_folder = database + '/' + country_ + connection_points

study_area = gpd.read_file(database+'/' + country_ + '/Study_area/Study_area.shp')
Clusters = gpd.read_file(cluster_folder)
# Clusters = Clusters[Clusters['final_clug']==final_clug]
Clusters = Clusters.to_crs(crs)
for ind, rows in Clusters.iterrows():
    Clusters.loc[ind, 'geometry'] = rows['geometry'].buffer(resolution_population*0.9)
Substations = gpd.read_file(substations_folder)
# Substations = Substations[Substations['final_clug']==final_clug]
Substations_crs = Substations.to_crs(crs)
# this can actually be done before, or with the html file

Substations['X'] = [Substations_crs['geometry'].values[i].xy[0][0] for i in range(Substations.shape[0])]
Substations['Y'] = [Substations_crs['geometry'].values[i].xy[1][0] for i in range(Substations.shape[0])]

if not os.path.exists(r'Case studies/'+case_study):
    os.makedirs(r'Case studies/'+case_study)
    os.makedirs(r'Case studies/'+case_study+'/Input')
    os.makedirs(r'Case studies/'+case_study+'/Output')
```


Appendix 4: Weighting and Creating a grid of points

```

1. CREATE A WEIGHTED GRID OF POINTS
C:\Users\Student\Desktop\Gisale-lesorho\Gisale-development\gisale\QGIS_processing_polygon.py:239: UserWarning: Geometry is in a geographic CRS. Results from 'buffer' are likely incorrect. Use 'GeoSeries.to_crs()' to re-project geometries to a projected CRS before calling.
  study_area_buffered=study_area.buffer((resolution*0.1/11250)/2)

EPSG:4326
EPSG:4326
EPSG:4326
EPSG:4326
(12493, 3)
| 180.01, 0.00, -153564.89|
| 0.00, -180.46, 3188151.49|
| 0.00, 0.00, 1.00|
Elevation finished
Slope finished
Population finished
Land cover finished
C:\Users\Student\miniconda3\envs\py3\envs\Gisale\lib\site-packages\pandas\base.py:36: UserWarning: The indices of the two GeoSeries are different.
  warn("The indices of the two GeoSeries are different.")
Protected area finished
12492/12493      X      Y ... Road_dist River_flow
0   -141825.23762  3.167379e+06 ...  400.337121
1   -141285.23762  3.167379e+06 ...  502.073771
2   -142005.23762  3.167559e+06 ...  165.717055
3   -141825.23762  3.167559e+06 ...  231.019522
4   -141645.23762  3.167559e+06 ...  267.015041
...      ...      ...      ...      ...
12488 -129405.23762  3.187719e+06 ...  298.143866
12489 -129225.23762  3.187719e+06 ...  477.908590
12490 -129045.23762  3.187719e+06 ...  587.639592
12491 -128865.23762  3.187719e+06 ...  408.017454
12492 -128685.23762  3.187719e+06 ...  228.988636

[12493 rows x 11 columns]
      X      Y ... Road_dist River_flow

```

Appendix 5: Clustering and location secondary substations

```
Gisele_script_new x
2. LOCATE SECONDARY SUBSTATIONS INSIDE THE CLUSTERS.
Sampling rasters finished
C:\Users\Student\miniconda3\envs\py3\envs\Gisele\lib\site-packages\geopandas\geodataframe.py:831: SettingWithCopyWarning:
A value is trying to be set on a copy of a slice from a DataFrame.
Try using .loc[row_indexer,col_indexer] = value instead

See the caveats in the documentation: https://pandas.pydata.org/pandas-docs/stable/user\_guide/indexing.html#returning-a-view-versus-a-copy
  super(GeoDataFrame, self).__setitem__(key, value)
0
Weighting the Dataframe..
Cleaning and weighting process completed
-----
The total costs for substations are 1.5 thousand euros
The maximum loading of a cluster is 43.603123850343884
The minimum loading of a cluster is 43.603123850343884
C:\Users\Student\miniconda3\envs\py3\envs\Gisele\lib\site-packages\geopandas\geodataframe.py:831: SettingWithCopyWarning:
A value is trying to be set on a copy of a slice from a DataFrame.
Try using .loc[row_indexer,col_indexer] = value instead

See the caveats in the documentation: https://pandas.pydata.org/pandas-docs/stable/user\_guide/indexing.html#returning-a-view-versus-a-copy
  super(GeoDataFrame, self).__setitem__(key, value)
Weighting the Dataframe..
Cleaning and weighting process completed
-----
Sampling rasters finished
0
Weighting the Dataframe..
Cleaning and weighting process completed
-----
The total costs for substations are 1.5 thousand euros
The maximum loading of a cluster is 30.087250078006235
The minimum loading of a cluster is 30.087250078006235
C:\Users\Student\miniconda3\envs\py3\envs\Gisele\lib\site-packages\geopandas\geodataframe.py:831: SettingWithCopyWarning:
A value is trying to be set on a copy of a slice from a DataFrame.
Try using .loc[row_indexer,col_indexer] = value instead
```