National University of Lesotho

Determining Cost Effective Integrated Renewable Energy Resource Plan for Lesotho (2022-2040)

Tsoarelo Nelson Nzemene: 199600284

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

Master of Science in Sustainable Energy

Offered by the

Energy Research Centre
Faculty of Science & Technology

July 2022

Abstract

The renewable energy potential for Lesotho has been sufficiently studied with only a limitation of which specific places could such energy be derived. The country does not have an integrated renewable energy plan (IRP) to help direct its efforts to address the problem of energy insecurity, low energy supply and over 50 percent dependence on electricity imports from South Africa and Mozambique. Most of the resources have been spent haphazardly and unprofitably in a bid to address access to energy problem. The objective of this study is to create an IRP that responds to cost effectiveness in Lesotho for 2022 to 2040 and to identify suitable places for renewable energy generation using Geographic Information System (QGIS) capabilities in order to increase the baseload capacity for Lesotho. These objectives were achieved by evaluating the existing renewable energy resources, especially solar and wind by determining suitable places for power generation to meet the ever-growing demand. This was achieved by first establishing the aggregated forecast electricity demand using the existing studies and this forecast formed the basis for envisaged future power demand for Lesotho. For example, the electricity demand is projected to reach 350MW in 2040. Secondly, proximity analysis results of the resource base to the grid, primary road infrastructure and substations at 3.5km and 15km buffer zones were done to determine suitable areas for renewable energy generation. The identified places were examined and the amount of energy that could be generated from them was estimated and evaluated. The findings showed that a total of 310MW added into the main grid cumulatively from both wind and solar resources from 2022 to 2040 would result in electricity supply independence for the country. The cheapest option in a generation was given first priority in terms of when to enter into the generation stream to meet the existing demand during scheduling in the determination of the optimum IRP. The study recommends a progressive reduction of imports since they can serve as safety buffers of the electricity network in the event hydropower is not sufficiently developed. The energy policy, renewable energy policy and other energy supply and demand instruments will be profited by this study.

Acknowledgements

My sincere gratitude first goes to my Heavenly Father for His untold mercies and special guidance during the MSc journey. I owe much thanksgiving to my Supervisors, Prof. B. M. Taele and Prof. Leboli Z. Thamae; Professors at the National University of Lesotho and Dr Albert Butare, Senior Advisor to the Ministry of Energy and Meteorology under the project “Support to Energy Sector Reforms in Lesotho”, your efforts made this work a success. My heartfelt gratitude goes towards my family for allowing me to go back to school. The resources you sacrificed for supporting my studies will be greatly recompensed. I cannot forget Room 802; colleagues you know yourselves, where could I have been if it had not been for your willingness to spend nights there. You were really great! “We go forward as a block”.

Contents

List of Figures

List of Tables

Chapter 1: Introduction

1. 1 Background

Lesotho, has for several years, been trying to address the problem of energy security [1]. Several documents have been developed using international and local consultants such as the Lesotho Energy Policy 2015-2025 [2], Electrification Master Plan 2018-2028 and several other documents to plan for reliable, safe and affordable electricity supply. This was with the aim to plan for reliable, safe and affordable electricity supply. Most of these plans have not been executed as anticipated. As a result, the problem of energy security is still looming in the country because more than 50 percent of peak demand is met through imports from Eskom - an electricity company in South Africa and Electricidade de Moçambique (EDM) based in Mozambique [2]. These documents did not capture how best the country can make use of its abundant renewable energy resources in a well thought through, coordinated, systematic, integrated and cost effective manner. This could be one of the reasons why up-to-date all these efforts have been unfruitful.

The installed capacity in Lesotho is not able to meet the maximum peak demand of 160 MW reached in 2019 [3]. It is anticipated that the peak demand will continue to increase in the near future given the continued effort of the Lesotho Electricity Company (LEC) to connect households and institutions. The electricity connections in the households will also continue to increase due to political influence of seeking to score a political point among the electorate and the general preference of the people to be connected to national grid. If there is no generation investment undertaken, the country's ability to meet its electricity peak demand will be completely eliminated.

The absence of a scientific robust integrated renewable energy resource plan for the country that clearly stipulates how best the country can make use of the abundant renewable energy resources available to meet its increasing energy needs, is a major setback to its self-sufficiency in power supply. Integrated resource planning is a power supply planning process that considers demand-side and supply-side options, minimizing the costs accruing to the firm and to society [4]–[6]. In the power sector, IRP can be explained as "an approach through which the estimated requirement for electricity services during the planning period is met with a least-cost combination of supply and end-use efficiency measures, while incorporating concerns such as equity, environmental protection, reliability and other country-specific goals" [4] [7]. Furthermore, IRP seeks to find an optimal combinations of demand and supply- side measures that will satisfactorily meet the power needs of the service area [8]–[10].

IRP may particularly be appropriate for developing countries where there are often severe capital constraints and untapped potential(s) for demand-side reduction [4], [11]. Demand-side control or management encompasses implementation of programs and activities that centre on the customer efficient use of electricity, time of use and interruptible rates [8], [12]. The IRP approach integrates equitable access to and a sound sustainable use of resources within the country. It provides utilities and power sector decision makers with handy tools to make informed decisions regarding power generation, transmission and distribution, thus enhance customer satisfaction [13]. It also allows utilities and energy planners to consider smaller generation options on an equal basis with central supply options. These smaller scale sources include mini-grids, cogeneration and demand side management (DSM) [14],[16],[17]. An informed decision of which investment direction should be taken by the utility or government agency can be reached within a limited time because all options will be laid plain on the table.

It is also worthwhile to consider Least Cost Utility Planning in Power Systems [16] . The Least-cost resource planning is a new way for utilities and state regulatory commissions to consistently assess a variety of demand and supply resources to cost-effectively meet customer energy-service needs. This planning paradigm differs from traditional utility planning in at least four ways:

(1) It explicitly includes conservation and load-management programs as energy and capacity resources,

(2) It considers environmental and social factors as well as direct economic costs,

(3) It involves public participation, and

(4) It carefully analyzes the uncertainties and risks posed by different resource portfolios and by external factors. Neither this method of planning nor IRP have been done for Lesotho.

1.2 Problem Statement

Electricity is considered a key socio-economic development driver that can boost the economy of Lesotho. The local electricity generation is mostly based on hydro and it does not meet the country's demand. Despite all the efforts to try to address the energy needs of Lesotho by the department of energy, much needs to be done to reduce more than 50% of electricity imports into the country. The fact that remains is that several studies have revealed that the country has an abundance of renewable energy sources. For example, the study on the potential of solar energy for both thermal and solar PV, have revealed that there are 300 days of sunshine in Lesotho with solar radiation regime at an average of 20–24 MJ/m2/day on the horizontal surface [17]. In spite of this great potential, there is little use of solar energy in Lesotho. There are plans however to bring on the line 90MW grid connected solar power and more than 20 solar power mini-grids production. When these are operational, there would be a paradigm shift in the electricity supply of Lesotho.

As of 2007, there were 1100 solar PV systems in Lesotho which were used compared to about 400,000 households existing then, as declared by [17]. This is a clear indication of low access to energy despite a high abundance of natural resources in the country. The absence of an integrated renewable energy resource plan with specific investment guidance highlighting the economic viability of each resource option is a teething problem in the country. It has led to a haphazard way of addressing the access to clean and affordable energy problem. This research seeks to close this gap.

Countries should be able to supply most of their citizens energy needs from local resources to attain energy security [18]. Where this is not achieved, countries import power from other countries by entering into different expensive contractual agreements. The power purchase agreements [19], [20] may not favour the importing country as it is the case with Lesotho and Eskom from South Africa. It should be noted that in most countries, a reliable energy supply is considered as an essential service.

1.3 Research Questions

The main research question to be answered by the study is: What is the integrated renewable energy resource plan that would respond to cost effectiveness in Lesotho for 2022 to 2040?.

The following subsidiary questions which emanate from the main research question were answered in order to address the main research question.

- What renewable energy resources exist in the country?
- How may the country direct its investment in harnessing the renewable energy resources to meet its ever increasing energy demand in a cost effective way and improve energy security?
- Which renewable energy resources mix option is the least costly and most suitable that can be embarked on by the country within an 18 years’ time period?

- Which places in the country are most suitable to be exploited in order to address the ever growing electricity demand?
- What export potential for clean energy trade within the Southern Africa Power Pool (SAPP) does the country see if Lesotho has to meet its objective of power self-sufficiency and exports?

1.4 Objectives of the Study

The main objective of this study is to design an integrated renewable energy resource plan for Lesotho. This objective was achieved through:

- An assessment of renewable energy resources in the country (Lesotho's renewable energy profile) through the use of Quantum geographic information system (QGIS)
- A desktop evaluation of projected electricity demand for Lesotho from different studies that cover the study period
- Spatial analysis in the QGIS of the existing power grid in relation to the renewable energy sources profiles, taking into consideration the road network, the terrain and communities spatial distribution
- Proximity analysis to the grid and substations to determine the low cost possibility of power wheeling.
- Modelling of the renewable energy sources to determine an optimal mix
- Providing a schedule for investment in order to address the energy deficit

1.5 Justification

The country does not have a cost effective integrated renewable energy resource plan to direct the funding for increasing access to energy supply in order to address its ever growing energy demand. The absence of this important tool means that a lot of funding may be spend in an uneconomic manner. This is further corroborated by Senatla et.al when indicating that a key starting point for increasing the baseload generation capacity for Lesotho is to put in place a practically and economically feasible integrated resource plan [21]. Also, desirable economic progress might be forfeited due to misdirected investment. Funding from the Ministry responsible for energy that has long been directed to the national utility (LEC) every year to electrify commercially viable areas will be better managed. The same reason applies to the Rural Electrification Unit (REU) which connects and electrifies rural areas and other areas outside LEC service territory. The disbursement of the fund in relation to electrification efforts, has to a large extent been a sole discretion of these institutions. There has never been a proper plan directing the Department and the Country at large as to how to address and close the ever looming demand and supply gap using the available renewable energy resources in a cost effective manner. The IRP will inform and direct the government in designing good policies including the Power Generation Policy, the Energy Policy and the Renewable Energy Policy.

1.6 Research Structure

The study included the following chapters: Introduction which explains the energy background of Lesotho and includes the problem statement, the main and sub-research questions, and justification of the study. Literature review followed touching on all relevant academic researches and national reports on IRPs and then Methodology chapter explained out how the analysis of resource data was be carried out. Afterwards, the Results and analysis of findings were presented. Conclusion and Recommendations is the last chapter.

Chapter 2: Literature Review

This chapter focuses on highlighting the current global and local state of energy. Further issues relating to energy development and planning of IRP are stated. It is intended to give a broad range and diversity of ideas suggested by different scholars and researchers on how to design, implement and reap maximum fruits of a well-planned out and executed IRP. The benefits and Challenges associated with adopting IRP as a planning tool in power sector planning and particularly for Lesotho, are explored. The methodologies that can be adopted in undertaking IRP by utilities and the energy sector, are discussed and compared, especially those that are relevant to Lesotho.

2.1 Global energy view

"The share of renewable technologies meeting global energy demand is expected to increase by a fifth, reaching 12.4% in 2023" [22]. This indicates that the world is recognizing the important role the renewables play in contributing to the global energy share. The global decrease in prices of renewable technologies is also a major contributing factor to the increase in the uptake of renewables. In the power sector, renewables accounted for half of annual global electricity generation growth, led by wind, solar PV, and hydropower. In the first quarter of 2020, deals to the tune of 1.76 GW of renewable capacity were signed by companies. Despite the Covid-19 pandemic, the renewable energy industry growth path remained unruffled and intact [6] clearly signalling that clean energy is increasingly becoming indispensable despite the constraints imposed by economic slowdown.

2.1.1 Solar PV

Solar PV growth is also spurred by distributed generation. Globally, Solar PV capacity expanded the most (97 GW) compared to other renewables, over half of which was in China in 2017 [22]. By the end of 2019, enough capacity of solar was in operation worldwide to produce an estimated 2.8% of global electricity generation [23]. In Lesotho, according to [17] , the success of solar technology hinges on financial incentives available to make such technology affordable and available for the people that need it the most. Lesotho is endowed with a vast solar potential to tap into for its energy supply and security. The study undertaken by the Italian National Agency for New Technologies and Energy and Sustainable Economic Development (ENEA) under the project "Renewable Energy Potential Maps for Lesotho" indicates that photovoltaic power potential for Lesotho ranges from greater than 1600- 1900 (kWh/kWp).

It is also envisaged that globally, the future cost of solar energy will be declining as argued in International Renewable Energy Agency (IRENA) [24]. This is further proved by Table 1 which shows clearly that the future cost of investing in solar energy production is predicted to be declining. Some of the factors contributing to this predicted decline include the fact that many countries are pushing for increased uptake of renewable energy in their local energy mix. There are also incentives introduced for companies to invest in renewable technologies ranging from feed-in tariffs, investment subsidies, tax credits, portfolio requirements and certificate systems [25]. Other reasons adding to this effect are economies of scale, increased competitiveness and maturity of the renewables sector [26]. These factors are directly encouraging increased adoption of renewable energy sources.

Table 1: International Renewable Energy Agency (IRENA) Forecast of Cost of Solar Energy Production at Utility Level (adapted from [24]**)**

Year	2010	2018	2030	2050
USD/Kwh	4 621	1 210	834 – 340	481 – 165
Average USD/Kwh	4621	1210	587	323

2.1.2 Wind Energy

Globally, the wind power market is expanding such that in 2019 it constituted 19% of the global energy share amounting to 60 GW [23]. The countries that are quickly up-taking wind technology and providing enabling environment in terms of change in policy are China and the US. There is also a significant increase in wind energy use in Europe. Table 2 presents the international comparisons of wind power capacity. It is clearly shown from the table that China has installed twice the wind power capacity than the US. In Lesotho in 2019, the Italian National Agency for New Technologies and ENEA under the project “Renewable Energy Potential Maps for Lesotho” produced a wind power density map for the whole country which indicated that Lesotho has a potential starting from “greater than 25 W/M^2 to greater than 1300 W/M^2” of wind energy. Thus, indicating that Lesotho can significantly generate some of its needed power from this resource as well as contribute to the global wind energy share if enough investment is directed towards this form of energy.

Table 2: World Cumulative Wind Capacity installed in 2019 (adapted from [26])

Annual Capacity 2019, MW		Cumulative Capacity end of 2019, MW	
China	26155	China	23640
United States	9137	United States	10559
United Kingdom	2393	Germany	6140
India	2377	India	3750
Spain	2319	Spain	2585
Germany	2189	United Kingdom	2334
Sweden	1588	France	1664
France	1336	Brazil	1545
Mexico	181	Canada	1341
Argentina	931	Italy	1040
Rest of World	10639	Rest of World	10467
Total	**60345**	**Total**	**65068**

Source: GWEC, AWEA WindIQ

Table 3 illustrates the international renewable energy agency (IRENA) forecast of future cost of wind energy production at utility level. These values were set considering policy targets and developments until April 2019 [27]. Any new policy changes and targets announced in the countries since then were not considered in the analysis and therefore could influence the findings presented in the table. However, these values shall be applicable to the analysis in this study.

Table 3: International Renewable Energy Agency (IRENA) Forecast of Cost of wind energy production at utility level (Adapted from [27]**).**

Year	2010	2018	2030	2050
LCOE (USD/kW)	1913	1497	800 – 1350	650 – 1000
Average LCOE (USD/kW)	1913	1497	1075	825

2.1.3 Hydro Electricity

Lesotho solely depended on Eskom for electricity supply from the 1970's until 1998. A decision was made around 1980s to explore electricity production using locally available renewable energy sources after a crisis ensued when the then apartheid government in South Africa decided to cut off electricity supply to Lesotho. Hydropower energy has been made use of in Lesotho since 1980s when mini-hydro stations were established in Mant'sonyane, Tlokoeng, Tsoelike and Semonkong. However, most of these power stations have been decommissioned due to non-functionality caused by siltation and prohibitive maintenance costs [17], [28]. The remaining ones are Mant’sonyane and Semonkong. Semonkong is a hybrid power station consisting of 180kW hydro generator and 120kVA diesel generator. Even this station runs more on diesel than on its counterpart hydro-generator, thus indicating the severity of challenges faced by Hydropower in Lesotho. Senatla et.al argues that hydropower can only be a viable option for Lesotho if investment is done in building large hydropower dams and power stations [21]. This argument still has to be proved since siltation seems to be a major problem of dams in Lesotho, even the current LHDA reservoirs are faced with the similar problem. The country is currently exploiting only minimal amount of its hydro potential of which the greater percentage is at the ‘Muela Hydro-power station.

The ‘Muela hydro power plant owned by Lesotho Highlands Development Authority (LHDA), with installed capacity of 72 MW, was completed and commissioned in 1998. The building of this hydro-power station resulted in the commencement of significant indigenous production [29]. A study was also commissioned by the Lesotho Department of Energy to evaluate the hydro potential of Lesotho and it was found that the country could potentially produce 450 MW in hydropower and several hundred more with wind power [28]. The Italian National Agency for New Technologies and ENEA produced a hydrological map for Lesotho with elevation ranging from 1400m to 3500m. These maps were done for assessing Lesotho’s renewable energy potential.

Despite all these efforts, the energy sector in Lesotho is still facing great challenges that need urgent attention. Some of the hurdles in the sector include very low access to energy, lack of security of energy supply, stagnant generation capacity and problems in the maintenance of facilities contrasting with rising demand, electricity import dependency from Mozambique and South Africa and a complete dependency on South Africa for Petroleum products. There is also a weak policy and institutional framework lacking holistic approach and incentives for private sector involvement and low awareness of renewable energy technologies and limited knowledge of potential resources. The IRP proposed in this study will seek to solve some of these challenges.

2.2 Energy Infrastructure Development

It is very clear that energy infrastructure will continue to be constructed for the foreseeable future in order to meet the growing demand of end-users and support the clean energy strategy [30]. There must, however, be a modality or guidance as to what to build, how to build and when to build. This calls upon countries to examine the nature of natural resources they are endowed with, the best means of exploiting them without damage to the environment and the cheapest ways of deriving benefits from them. Lesotho needs to invest in its natural resources and build energy infrastructure for the good of its citizens.

2.2.1 Economic Impacts of investment in Energy.

Energy industry plays a key role in greenhouse gas emissions in the world, especially in China which contributes more than half of the world greenhouse gas emissions [31]. Investment in the energy industry plays a crucial part in promoting the low-carbon development which proves to be good for many economies and the populace at large. As stated by [31], the energy investment in renewables can also provide reduction of carbon intensity of energy industry and stabilize the total greenhouse gas emission in energy sector. It is however argued that developing countries need to use carbon intensive energy sources for them to reach the stage of developed countries as seen in the case of China's use of coal [32] [33]. This will mean development of renewables will not be a priority in such countries especially if they are naturally endowed with carbon intensive energy sources.

2.3 The Importance of IRP

The importance of the IRP cannot be overemphasized. It bridges the gap between demand and supply. Many problems beset the developing countries like Lesotho with hurdles such as poor access to clean energy for rural and urban households, unaffordable energy prices due to low earnings, insufficient financial resources for investment in such non-lucrative sectors, inefficient transmission and distribution systems, and inadequate environmental protection [13], [34]. Many of these problems can be addressed through implementation of IRP. In "Electricity Expansion Plan for Lesotho", Senatla et.al agree with the foregoing assertion that the starting point in addressing the electricity deficit in Lesotho to meet both the baseload and the peak demand would be to come up with a practically and economically feasible Integrated Resource Plan [29]. Even though Senatla et.al indicate the times when renewables can enter the energy supply chain in the country, she does not specify nor indicate a systematic way of implementing an IRP in Lesotho and materially leaves out where such renewables can be sourced. This research seeks to close that gap by assessing the existing renewables resource base and indicating the possible places where these can be exploited within the specified proximity of LEC grid.

2.3.1 The difference between traditional power system planning and IRP

The failures of the energy market have led to new planning approaches of the energy sector especially for utilities. These planning methods are contradistinguished from traditional power systems planning methodologies. In traditional power system planning, the load forecast is determined and then demand for future electricity is fixed prior to the analysis of resource options [35]. In this planning methodology, the loads are specified exogenously and exclude non generation options such as energy efficiency measures. This is a great handicap to traditional planning because energy efficiency measures can help curb a lot of demand when implemented in a larger scale. This can serve as a desirable and most immediate measure of controlling the rise in energy demand. Traditional planning focuses mainly on the supply-side resources to meet the future demand. The benefits that accrue from inclusion of demand-side resources are forfeited in this planning framework. The path way of undertaking the traditional power system planning is shown in Figure 1.

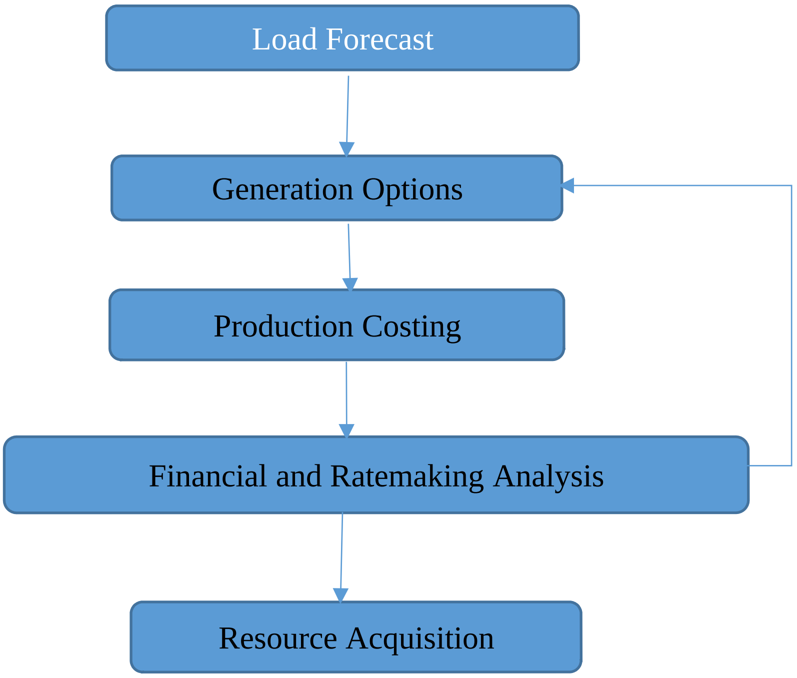

Figure 1: Traditional Planning Methodology Path adapted from [35].

On the other hand, according to [4], [35], in integrated resource or least-cost planning, non-generation options are explicitly included as options for utility intervention. Consequently, the load forecast becomes endogenous to the planning process. Integrated resource planning differs from the traditional planning model in that it also includes societal costs such as environmental impact mitigation. It is also technologically neutral, treating demand-side options, end-use efficiency improvements and demand-side management with the same degree as supply side options thus equating deferred or avoided end-use demand of electricity with generated supply of electricity [4]. This gives rise to the concept of avoided costs. Avoided cost is the cost an electric utility would otherwise incur to generate power if it did not purchase electricity from another source [36]IRP provides an avenue for assessing the potential for various cost avoidance strategies [36]. The goal of avoided-cost analysis is to help managers realize opportunities not to spend. Thinking about how to avoid costs can help overcome the bias toward supply-side options inherent in the traditional planning process. IRP further allows for an integrated assessment of supply and demand-side options of increasing energy services, attempting to minimize all costs, and creating a flexible plan that allows for uncertainty and adjustment in response to changing circumstances. The systematic approach that undertaking IRP should follow is depicted in Figure 2.

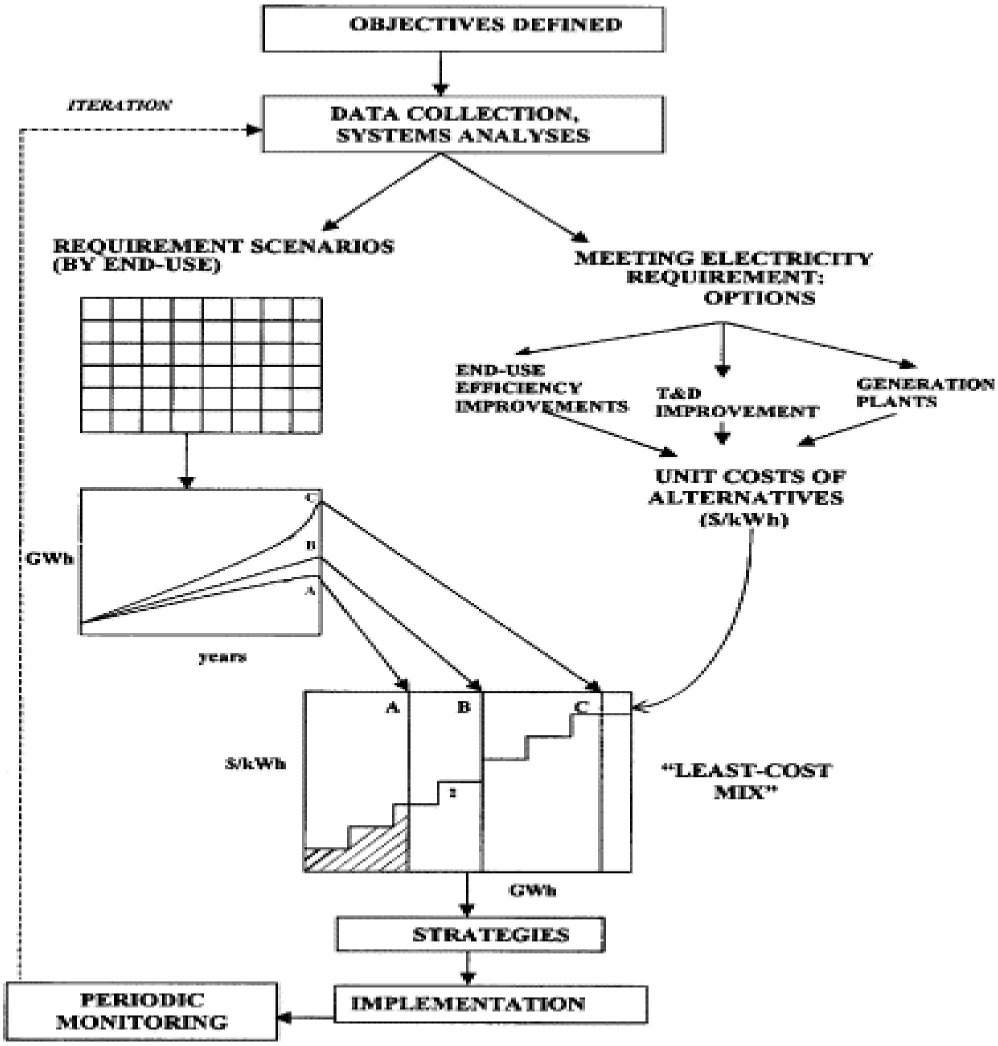

Figure 2: Steps in the IRP procedure adapted from [34]

The IRP process can be summarized as forecasting, assessing options, constructing a plan, evaluating a plan and reviewing the plan [37]. All these activities are linked as illustrated in

Figure 3. The quality of the plan is strongly dependent on the quality of and availability data. The analysis undertaken in each activity is also a major factor in the quality of the plan.

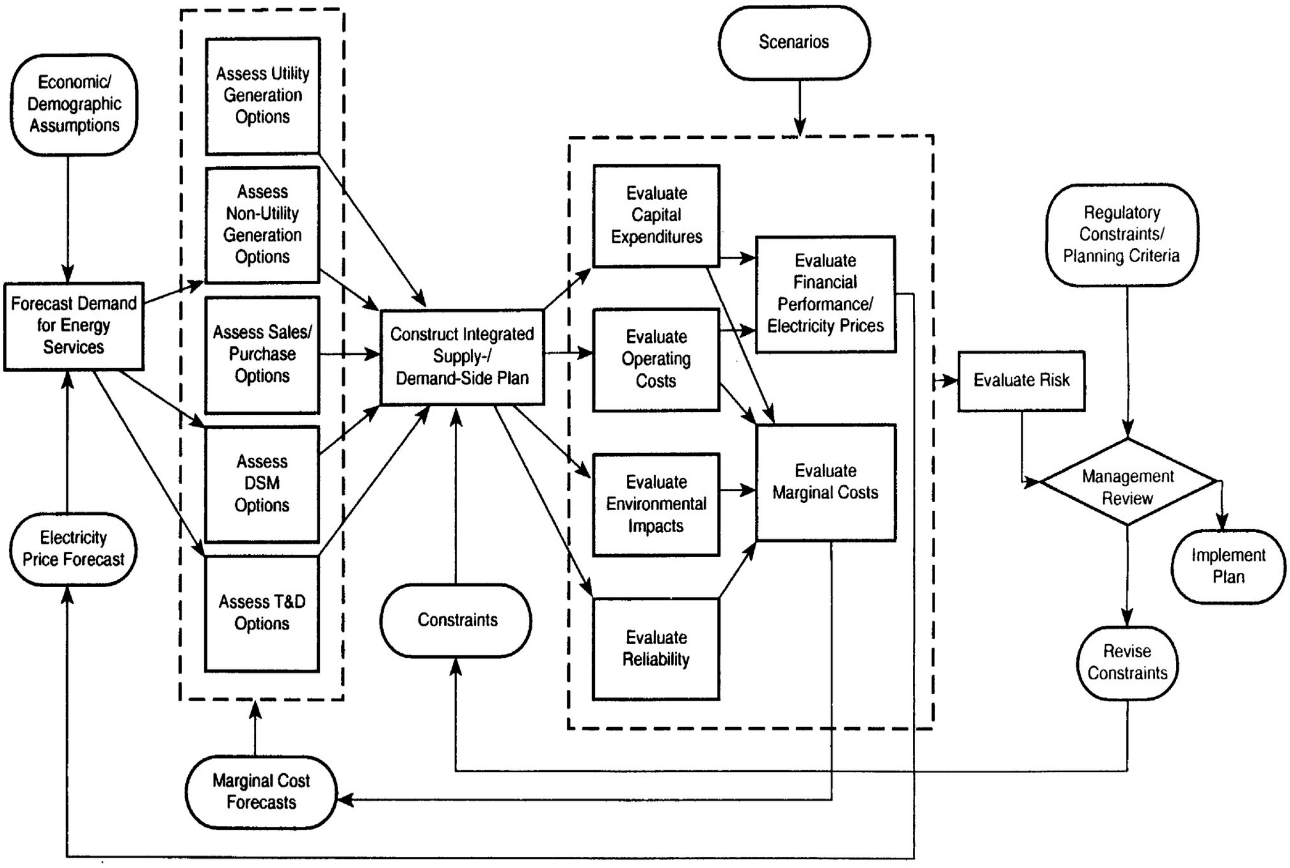

Figure 3: IRP Planning Process adapted from [37]

2.4 Planning Models in Implementing IRP

It is important to note that originally, planning models were designed to be stand-alone, each model with its own unique set of inputs and outputs and corresponding data conventions. The idea of linking them with each other was foreign to the original framework. This introduces a complexity in undertaking IRP or Least Cost planning because each step in the process can actually be evaluated using a model. Such a model may not, in any way, be linkable to the models used in succeeding steps. Numerous models exist that can be employed in each step of the IRP processes including load-shape forecasting, generation planning, production costs, financial analyses, and rates [38]. For instance, most of the load forecasting models fall under Time series, Artificial Neural Networks and bottom up end-use Approaches. No load forecasting models can be deemed to be superior to others. The purpose and the time frame for load forecasting will inform which models will be appropriate to use. In many instances, according to [38], the simpler the method, the better.

2.4.1 Load-shape forecasting models

Most of the load forecasting models fall under Time series, Artificial Neural Networks and Bottom-up end-use Approaches.

(a)Time series analysis

Autoregressive Moving Average (ARMA): The basic ARMA model is composed of an autoregressive model (AR) and a moving average model (MA) [38]. The autoregressive model is a linear regression of the current value based on one or more previous values. The MA is a linear regression, at the difference that it regresses current values against the white noise or errors of one or more past values. It is stationary. If not, the stationarity can be achieved by differentiating a non-stationary series in first place hence resulting in Autoregressive Integrated Moving Average (ARIMA) [38].

The advantages of using ARMA method for load shape forecasting are that it is adaptable, can deal with seasonality and with non-stationarity and only requires the past value of a time series. However, disadvantages are that it is unlikely to perform well on long-term prediction, the computation takes a long time and it is a subjective model that requires a good understanding of the underlying statistics.

(b)The Artificial Neural Networks (ANN)

The ANN is an intelligent machine learning method based on the structure of the human brain. One of the most commonly used ANN is the Multi-Layer-Perceptron. This multilayer network is based on a back propagation rule which evaluates the output’s error and reduces it, adjusting the weights by back-propagating the error from the output to the hidden layer [34]. ANNs are particularly suited for energy forecast. They provide a good estimation in cases where data is incomplete [38].They can address complex nonlinear problems while demonstrating robustness and fault tolerance. It is a data-driven self-adaptive model that includes pattern recognition and captures subtle relationships, deals with noise and does not depend on the programmer's prior knowledge of rules [39].

The down side of the ANN’s results is that they cannot be easily explained as they are not mathematically based, the computation is time consuming, and training process optimization is complex and requires extended data. Again, the model may never converge in some cases. The odds in using this method far exceed the benefits in Lesotho’s case. Again, sufficient data from the utility is available to project the future demand.

(c) Bottom up end-use approach

This approach evaluates the probability for a specific appliance to be “on” at every time step of a day by considering various factors involving the appliances and household members’ characteristics [39]. A calibration is applied to this probability considering whether the activity can be done by the person available, the number of people the activity requires, and whether the activity can be done simultaneously with another activity. This modeling is advantageous in that it considers behaviour of the various types of customer and lifestyle-related psychological factors. It also describes interrelations between appliances and members of the household and is easily understandable. It can additionally deal with missing values and its maintenance is simple.

The flip side is that a large number of data and tenants behaviour surveys are required. In reality, there is lack of information regarding customers’ behaviours in the long-term, thus, inherently inaccurate in the long-term. The model also assumes a constant relationship between electricity consumption and end-use [38], [39].These models are short term planning models and would be appropriate for the planning horizon of this study. However, no specific model will be utilized to determine the energy demand forecast. Rather, logarithmic extrapolation in excel will be used to forecast the future energy demand for Lesotho.

Models and other analytical tools have value for Least Cost Utility Planning (LCUP) only to the extent that they facilitate planning by manipulating data in ways that are meaningful, understandable, and helpful to decision makers [38]. The key attributes that have to be considered during modeling of the renewables are capability, availability, efficiency, dispatchability, location, modularity, costs, incentives, risk-diversity and external costs [33]. Among these attributes, the most vital whenever renewable modeling is considered are capability, availability, location, modularity and risk diversity.

2.4.2 The planning models for IRP

There are many models that can be adopted in designing a utility of country’s IRP. The local situation surrounding the utility will dictate which method(s) will be most suited to use to design the IRP. Table 4 shows some the models that can be used and the functions they are most suited to address.

Table 4: Planning Models for IRP adapted from [33]

Model Type	Functions
Bulk power market	Forecasts quantities and prices of firm and non-firm energy available within a region
Capital expenditures	Forecasts capital requirements
Composite reliability	Calculates bulk power system reliability indices given a load forecast and generation and transmission capability and availability parameters
DSM cost-effectiveness	Assesses cost-effectiveness of individual DSM options
Econometric demand forecasting	Forecasts demand on a yearly or seasonal or hourly basis given assumptions about economic and demographic trends
End-use demand forecasting	Forecasts demand on a yearly or seasonal or hourly basis given assumptions about end-use profiles, appliance holdings and econometric trends
Energy sector model	Forecasts supply and demand interactions between different energy sectors of the economy
Financial/rates	Forecasts revenue requirements, rates, and financial indices
Generation reliability	Calculates generation reliability indices given a load forecast and generation capability and availability parameters
Load Flow	Evaluates the loading of transmission lines
Location benefits	Evaluates the avoided transmission and distribution costs attributable to a resource at a specific location
NUG forecasting	Forecasts from and payments to the nonutility(NUG) sector
Production simulation	Calculates generation, fuel use, production costs and emissions given load and fuel price forecasts and resource capability, availability and efficiency parameters
Project economic analysis	Evaluates the costs and net benefits of individual generation projects
Resource model	Evaluates potential for generation from a specific technology or category of technologies at a specific site or in a geographic area
Resource planning	Optimizes the selection and timing of resource options
Uncertainty analysis	Performs scenario, trade-off and/or probabilistic analysis

(a) Production Cost Models

These type of models are often used by the utility planners and system operators to inform their generation and transmission [40]. This portfolio of models is generally commercial and proprietary. Commercial production cost models are security-constrained unit-commitment (SCUC) and security-constrained economic dispatch (SCED) models that typically model the hourly or sub-hourly operation of all individual generator units in the model system for a given period. Some examples of these are PLEXOS, Gridview and GE MAPS.

2.5 Financial and Ratemaking Analysis

A rate is 'an estimate of the expected value of future costs'. Such rates are actuarially sound if they provide for all of the expected costs of the risk transfer and appropriately reflect identified individual risk characteristics [41]. The value of either solar or wind utility future cost is hinged on the estimated future value of these technologies done by IRENA [24], [27]. This is subject to unknown future shocks of the energy economy and price volatility. Abrupt changes in the world energy market such as was induced by CoVid19, can change the dynamics of the anticipated costs unpredictably. However, IRENA argues that solar and wind energy survived the shocks.

2.6 Resource Acquisition

The IRP cannot be implemented except there is acquisition of resources to actualise the plan. Acquisition of resources for the implementation of IRP is subject to regulatory frameworks applicable to each country. These resources can include electric generating units, transmission lines, contracts to purchase energy and firm capacity, rights to transmit and distribute electricity, and programs to implement (or incentivize) demand-side resources [42].

2.7 Energy Efficiency and Demand Side Management

Demand-side options refer to programs and activities designed to affect customer usage of electricity such as energy-efficiency programs, time-of-use and interruptible rates [8]. Energy efficiency investments tend to be incremental and have short lead times. According to [43] efficiency measures can be implemented and provide return to investment long before a power station can be completed. Efficiency measures can be employed to reduce the system peak demand (which drives the overall investment level) by providing incentives to certain categories of consumer to shift their demand from the peak hours of the day to the off-peak period.

2.8 Contribution of the Research

There are scarcely any issues mentioned in the literature reviewed concerning how to go about designing and implementing an IRP in the context of developing countries like Lesotho, looking at the available renewable energy sources. The literature seems to be lacking in this respect. In this research, an assessment of the resources that are available and have been identified will be done and places to be used for the resources utilization and energy production shall be specified. This research will contribute in providing a practical approach, design and implementation of IRP in context of Lesotho as a developing country, which seems to be lacking in the reviewed literature.

Chapter 3: Methodology and Material

The methodology to be adopted in undertaking this study entails collecting of input data files into Quantum Geographic Information System (QGIS) which mainly consist of renewable resources shapefiles from the Department of Energy as depicted in Figure 4. When these files have been input into the software, there would be desktop analysis of the resources in relation to the existing electricity and secondary road infrastructure to establish proximity relationships. The electricity demand forecast for the period of the study will be done. The other sections that are presented are: extrapolation of demand, criteria used for power supply, GIS map production, renewables mapping, renewables potential analysis from maps (Photovoltaic and Global Irradiation on Panel analysis, Hydropower analysis), proximity analysis, power generation (viable sites for possible PV or wind power generation at specified buffer zones) and optimum (least-cost) IRP procedure.

The steps followed in undertaking the study are illustrated in the following flow chart:

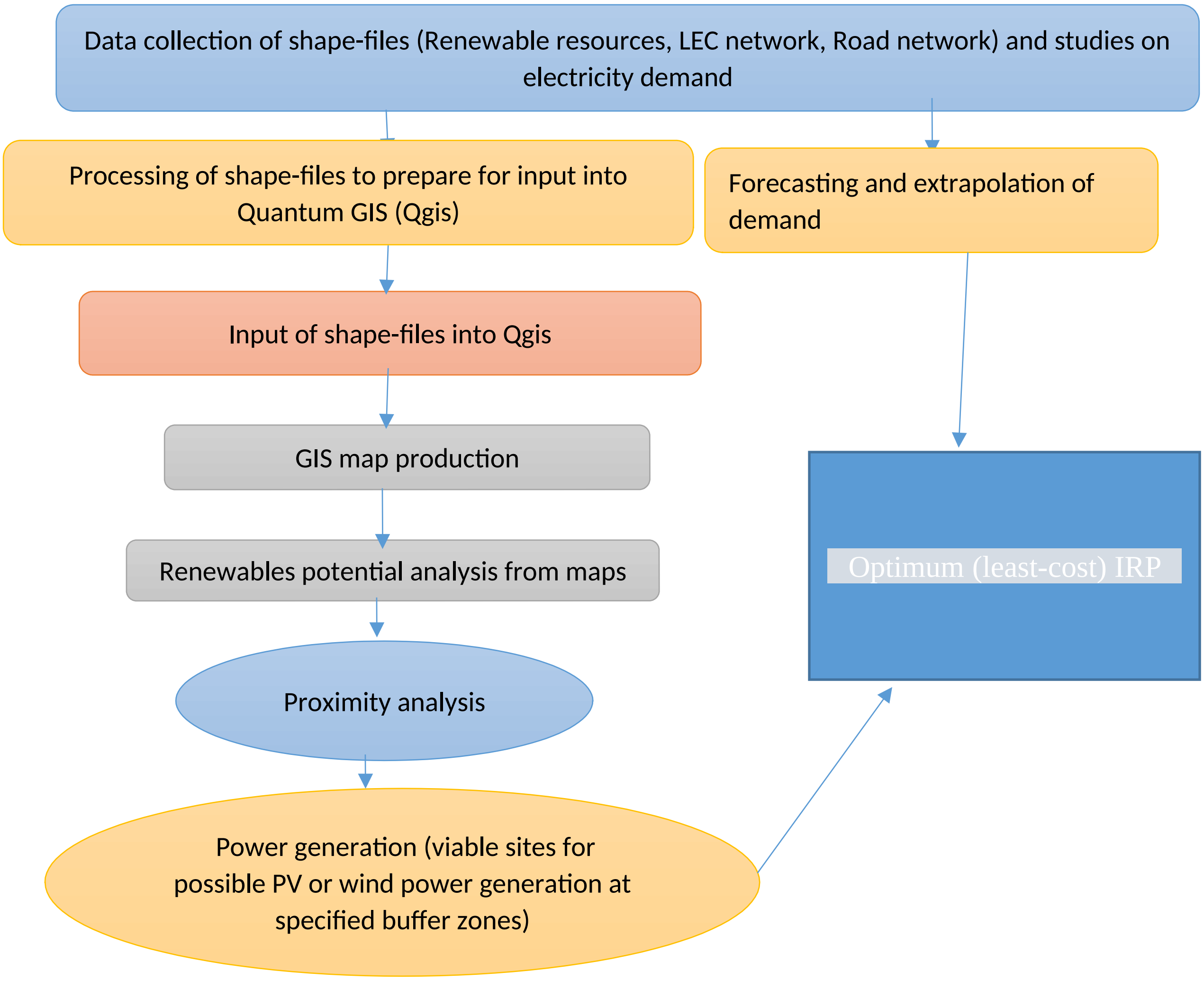

Figure 4: Research activities flow chart

3.1 Electricity Forecasting

Forecasts of electricity consumption and peak demand over time horizons of one or two decades are a key element in electric utilities meeting their core objective and obligation to ensure reliable and affordable electricity supplies for their customers while complying with a range of energy and environmental regulations and policies [39]. Such forecasts form the basis of utilities' capacity expansion planning, which consists of building or acquiring power generation plants, purchasing power from other sources, and other means of securing electricity supplies and services for their customers [39].

The electricity demand scenarios for Lesotho that satisfies the study period have been sufficiently studied and projected by several authors such as Senatla et al paper (PLEXOS – 2017 to 2050)[29], Mpholo et al (MAED – 2010 to 2030) [44], and Kente (MAED – 2020 to 2040) . For example, Senatla e.t al optimized the demand for Lesotho using ARIMA based forecasting model from 2015 to 2050 [29]. Table 5 presents ARIMA based forecast of demand for Lesotho as anticipated in the model used by Senatla et.al. The base scenario was the most preferred given the prevailing economic conditions in Lesotho cast by covid 19 pandemic.

Table 5: ARIMA Based Electricity Forecast for Lesotho (Adapted from [29])

ARIMA BASED FORECAST					
2015	**2025**	**2035**	**2045**	**2050**	**Year**
150	254	363	472	527	Peak (MW) Base
150	232	357	551	684	Peak (MW) High
797	1057	1291	1577	1706	Energy demand(GWh) Base
811	1345	2230	3499	4130	Energy demand(GWh) High

In the electrification master plan there is another dimension of electrical power demand projected for Lesotho [45]. In Figure 5, the maximum demand scenario is portrayed from the electrification master plan. There is a wide discrepancy in projected figures from both models used. For example, ARIMA estimates the maximum peak demand in 2025 to be 254 MW whereas EMP estimates it to be around 350 MW yielding a difference of 96 MW for the same year. These differences could be attributed to the underlying assumptions within the model, level of accuracy and other factors when computing these forecasts in the models.

This difference necessitated derivation of average maximum demand from cost of supply study demand forecast, ARIMA model demand forecasting and LEC actual demand which was used in extrapolation of the future demand as seen in Figure 13.

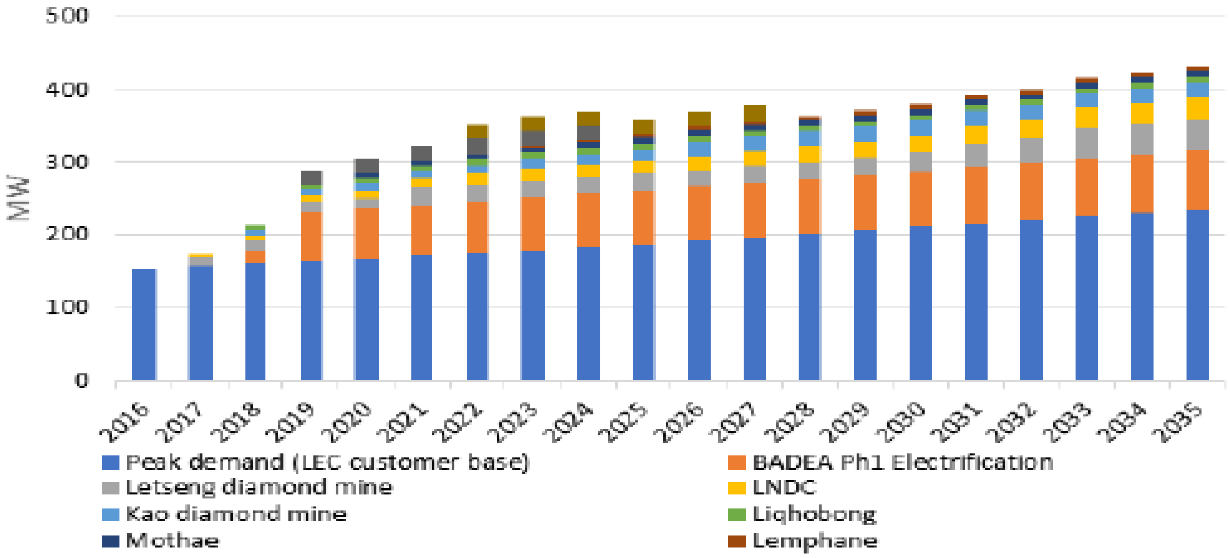

Figure 5: Maximum Demand Scenario (Adapted from [45])

3.2 Extrapolation of Demand

Extrapolation means predicting data that is not yet collected. The future electricity demand for Lesotho has been derived using logarithmic extrapolation. It resulted in a more realistic energy demand projection than the linear method. In order to curb these differences during the determination of the future demand, logarithmic extrapolation method was used instead of linear extrapolation. The basis of choice was that logarithmic graph seemed to align more smoothly with actual data than linear graph. Again, it seemed more agreeable to the existing and envisaged socio-economic developments.

3.3 Power Supply Criteria

The supply of the needed power will be determined using a multi-pronged approach employing the use of Geographic Information System (GIS) software in order to determine the most viable and suitable places which are exploitable and enriched with high renewable energy resources potential in Lesotho. The location of the places will give direction as to the feasibility of building renewable power generation plants in those particular places. The advantage of using the GIS for determining places for power location is that it uses location as the key index to relate seemingly unrelated data [46]. It is worthy of note that innovations in solar radiation mapping are now contributing to the rapid growth of solar energy market in many countries [47]. It is also crucial to find better places for installing solar energy systems for effective and efficient harnessing of the resource and to maximise returns to investment [47], [48].

The QGIS software used in analysis is open source. It is much simpler to attain and use than commercial ArcGIS and can still provide sufficient analytic functionality needed for this study. The shape files of the Renewable Energy Potential Maps for Lesotho were captured into a QGIS software and overlaid on the 2016 cartographic map for Lesotho available at Lesotho Bureau of Statistics (BOS) as depicted in Figure 12. They were also overlaid on the electricity reticulation map and electricity sub-stations map shown in Figure 6. Connection to the existing grid depends on substation configuration and the power plant output. For example, One Power (1 PWR), will connect at 33kV load side of the substation in the mini-grids it is implementing in the country, whereas the Ha-Ramarothole Solar Power Plant (70MW) will connect at 132kV of the supply side of the substation. 1 PWR will generate 1kV from panels, then step up to 33kV at inverter/transformer and directly connect to 33kV load side at the substation. The 70MW panels produce 1kV voltage which is stepped up to 33kV at inverter/transformer, then cable connection to substation, then stepped up again from 33kV to 132kV at substation in order to connect at 132kV supply side bus-bar.

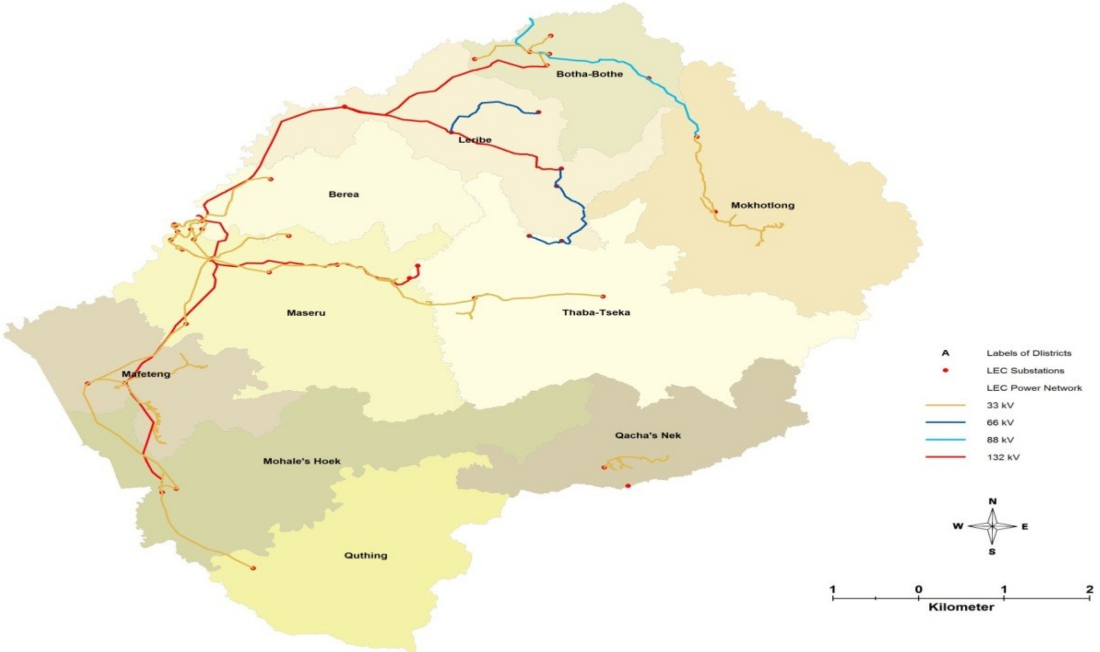

Figure 6: LEC Power Network (33kV-132kV) and substations (Adapted from LEC)

3.2 Map Production

Map shape files of each renewable energy resource received from Department of Energy (DoE) were imported into a QGIS software. The road infrastructure network shapefiles (maps) in Figure 7 and LEC power lines network shapefiles were uploaded into the software to enable analysis around these vector maps. Geoprocessing tools were employed to process the maps and produce the needed output. Although these maps have different projections, through the use of geoprocessing tools, a common projection was done as these maps were made to align before analysis could be done. After that, comparison and analysis of these different maps was done in order to determine how these maps relate with each other. The amount of energy that could be derived from identified places was approximated using the area of the identified place and the resource base values derived during map production.

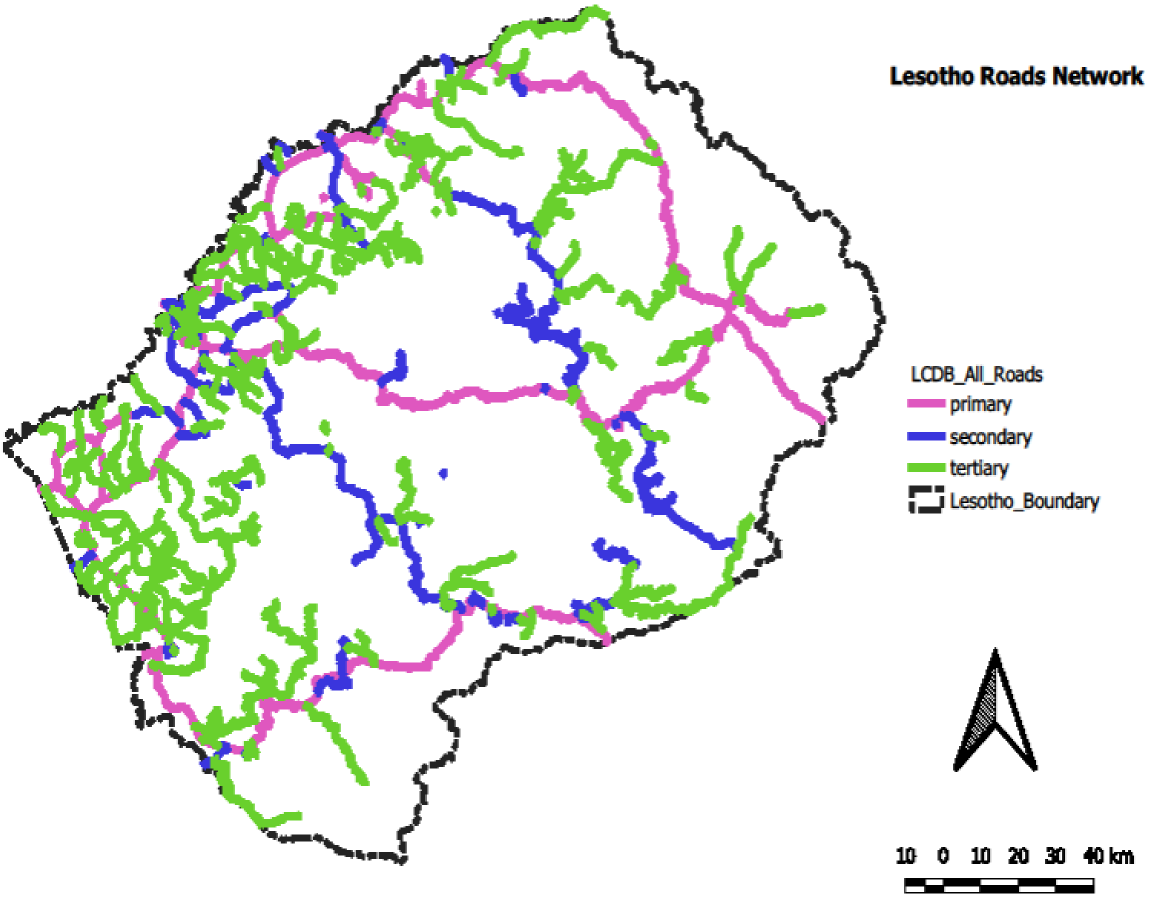

Figure 7: Lesotho road network and type (Adapted from DOE)

3.3 Renewables Potential Maps

The renewables potential maps to be analysed in detail include photovoltaic potential, Global Irradiation on Panel and wind energy maps. Hydro energy potential was not delved into in detail since it was not majorly evaluated in this study. The renewables profile maps depicted in Figure 8 and Figure 9 were overlaid on LEC power network consisting of lines that ranged from 33kV to 132kV and substations as portrayed in Figure 12 . This range of utility network was chosen on the basis of the present network capabilities of the utility and the constraints applicable to each line posed by its kilovolts rating.

3.3.1 Photovoltaic Potential Analysis

The methodology of analysis of photovoltaic potential adopted in this study was to take already created maps of Photovoltaic potential received from DOE into the QGIS software. A legend of the potential depicted on the map in different places of the country was created. The road network and LEC grid shape-files were overlaid on the PV potential map and proximity analysis to LEC using 3.5km and 15km buffer zones was done. The digitized area was estimated using the software. Looking at the legend, areas that showed medium to high PV potential were prioritized, digitized and analysed to estimate the amount of electricity that could be generated from the place. This also depended on performance of photovoltaic systems installed since their productivity primarily depends on the proper inclination and azimuth angle of the photovoltaic modules, shadings, and snow barrier [49] [50].

The solar potential map of Lesotho is shown in Figure 8 portraying variables that were captured during its design. On the map. Some of the variables of interest that could be derived are; solar optimal module inclination, global irradiation on panel (GIP) yearly average and photovoltaic power possible in different places. This map served as an input data into the Quantum Geographic Information System (QGIS) to do the analysis of solar energy potential. The variables given in the map were used to determine the amount of solar energy that could be derived in different viable places.

3.3.2 Global Irradiation on Pane (GIP) analysis

This analysis considers the optimum panel tilt for maximum production of Photovoltaic energy. The angle β represents the tilted surface inclination with respect to the horizontal plane. The optimum β was found through an iterative approach [51], [52]. The annual energy production for 30 years for each of the 15β ranging from 25° to 39° suitable for Lesotho was done. The process was then followed by an evaluation of average energy production of the 15 β values from which the optimum value was found. All these processes were followed to produce the GIP map which served as an input file into the QGIS software used for analysis.

The results in this analysis are based on the optimum PV module β angle inclination. The significance of the results from this analysis is that they have factored-in the β angle suitable for panels in Lesotho in different places which is more practical for investment than the general PV power analysis. However, all the results from both methods used are important for solar power analysis of the country.

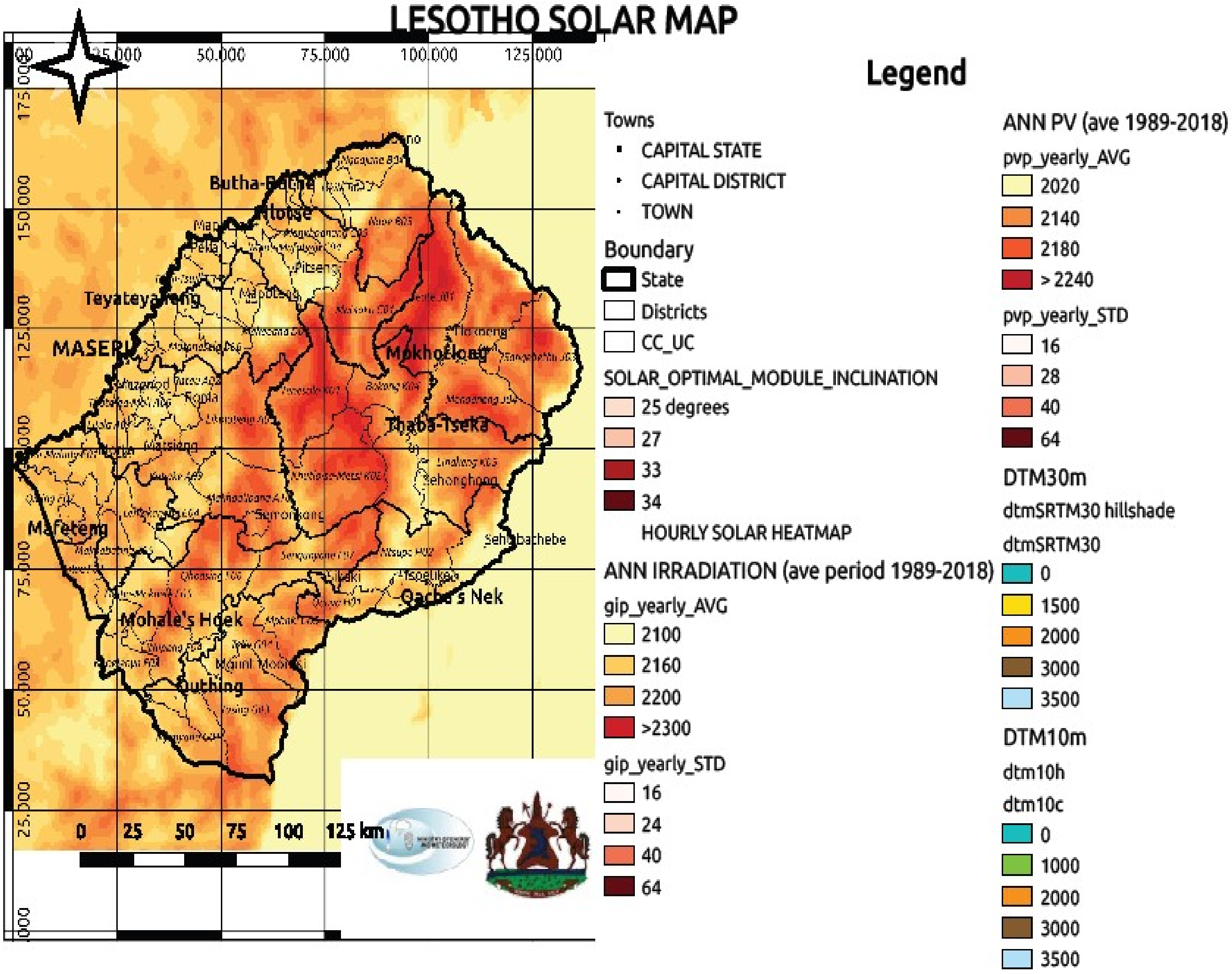

Figure 8: Solar Potential Map for Lesotho (Adapted from DOE)

3.3.3 Wind Energy Analysis

Figure 9 depicts the wind potential map of Lesotho at 200m mast height. This map was used for zoning the resource in relation to the LEC High Voltage grid (33kV-132kV) using 3.5km and 15km buffer limits. The primary road network map was overlaid with this map to establish accessibility to the areas where the resource is deemed more viable for power generation. These places have been selected and digitized to determine the area and reference coordinates.

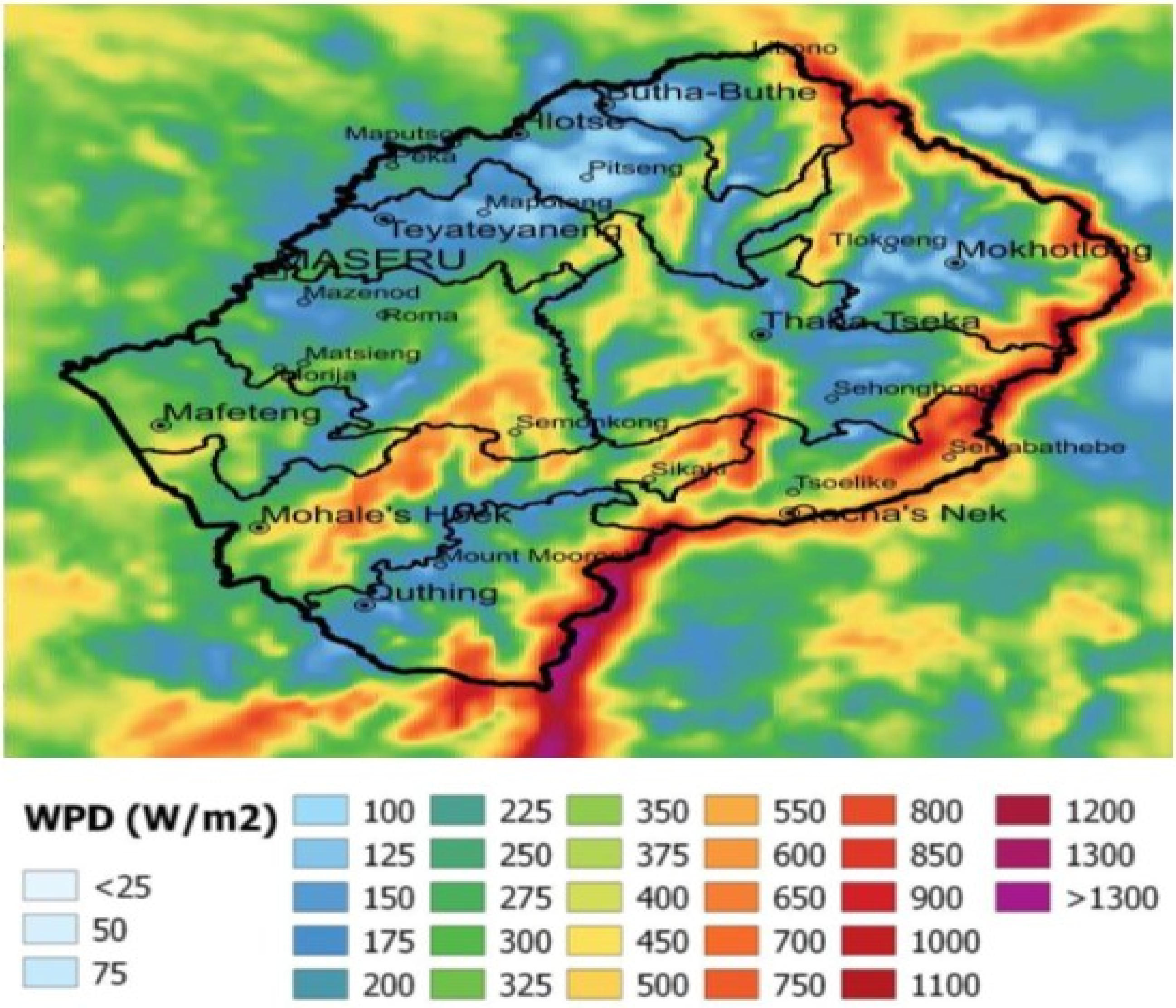

Figure 9: The Wind Potential Map for Lesotho at 200m of Mast height (Adapted from DOE)

3.3.4 Hydro Energy Analysis

The shape file map in illustrates Lesotho rivers network. The three primary rivers indicted in the map are; the Mohokare, Makhaleng and Senqu (Orange) rivers. They meander through many mountains that typically characterize Lesotho and that could serve to create good basins for large hydropower generation. However, it can be very difficult to put up sustainable hydropower generation along these rivers due to a high risk of siltation caused by soil erosion from fields upstream where most rural dwellers lead an agrarian lifestyle. There are also bottlenecks imposed by the international treaties Lesotho is party to especially regarding Senqu river basin. Orange-Senqu River Commission (ORESECOM) was formed in 2000 to manage the Senqu river basin resources, as such any major development along the river must be approved by this commission.

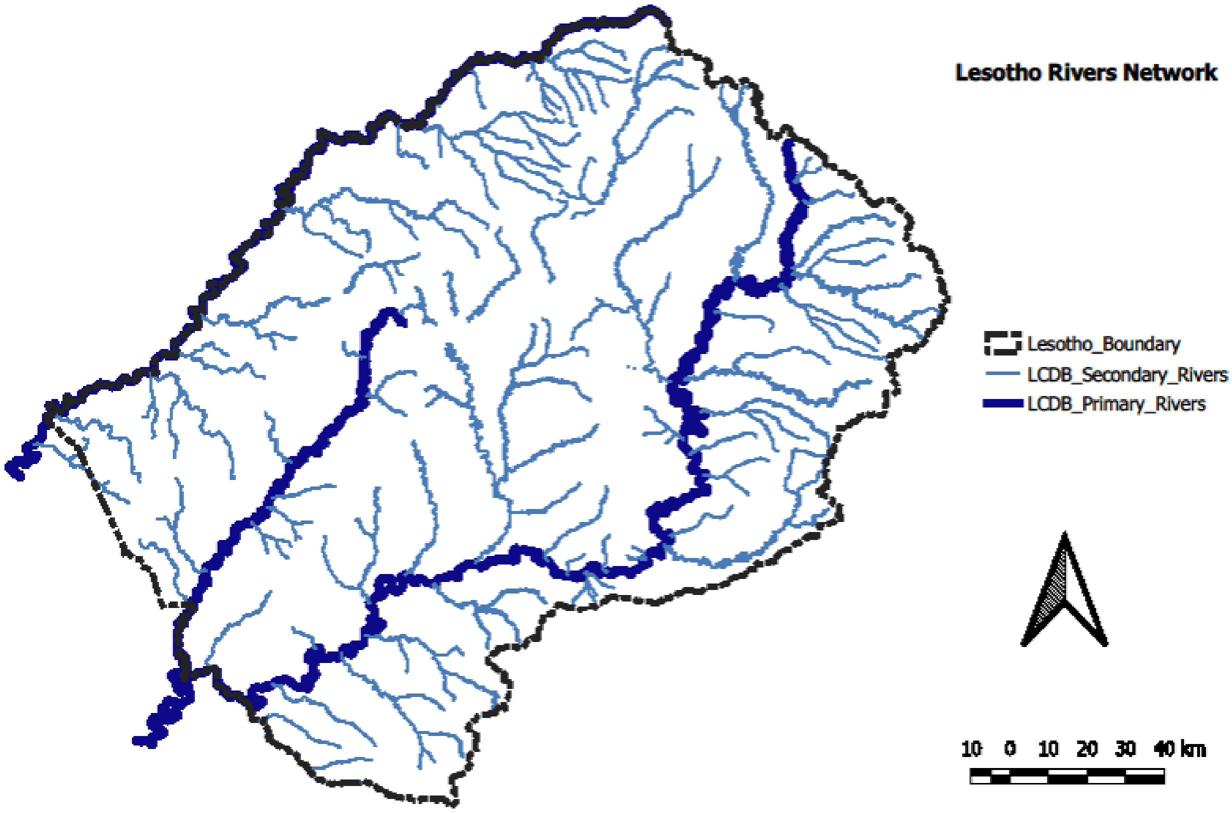

Figure 10: Lesotho Rivers Network (Adapted from DOE)

The hydrological map in Figure 11 shows the main reservoirs built in Lesotho by Lesotho Highlands Water Project (LHDA). These reservoirs serve as a basin for the supply of water to the Republic of South Africa (RSA). The wetlands and rivers that supply water in the catchments that lead to these water bodies are protected and need less interference. Hence, hydro energy production must not divert water away from these reservoirs. Therefore, any analysis of hydro energy production must take cognizance of these limitations on land use. The map available was not designed to give full hydrological information of Lesotho; rather it was meant to serve as knowledge base for energy planning. It cannot be reliably used for estimation of hydro potential of a given catchment, streams or rivers.

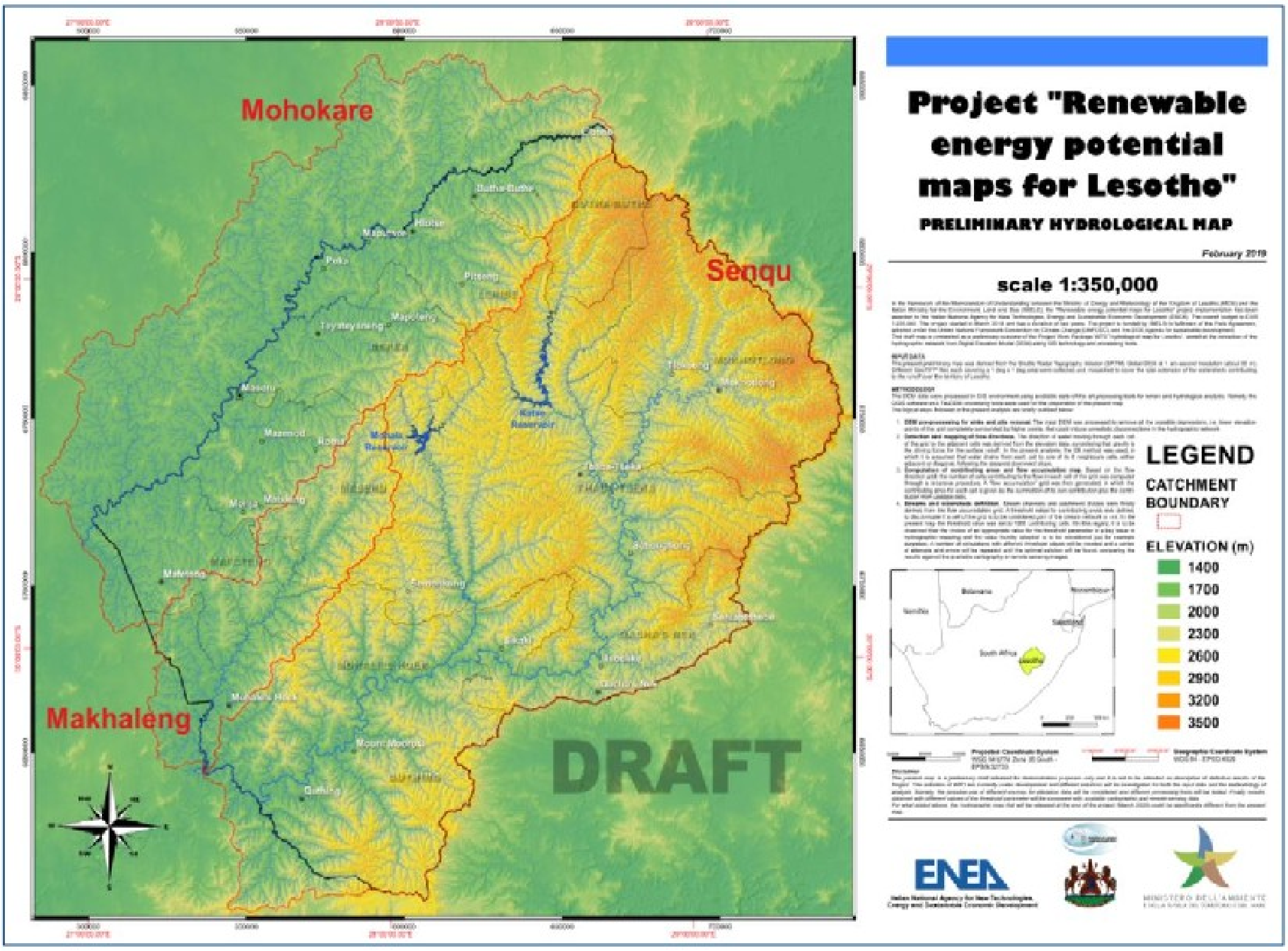

Figure 11: Hydrological map for Lesotho

3.4 Proximity Analysis

In order to carry out the proximity analysis in the Quantum Geographic Information System (QGIS), the platform was first launched in the computer before data processing could commence. The data layers to be analyzed were then loaded into the software in the form of shapefiles (.sh). Correction must be made, if need be, of projection and coordinate reference system (CRS) used for deriving different shapefiles so that they can be in the same format. For example, the LEC reticulation lines were developed under CRS LEC 27 reference system but were transformed to the World Geodetic System-1984 designated as CRS EPSG: 4326 WGS84 in the map attributes menu to facilitate overlaying. This system was developed by the now defunct European Petroleum Survey Group (EPSG) and is very much present in QGIS systems. The buffer process was run by accessing the menu in the software and following this procedure: TOOLS -> Geoprocessing Tools -> Buffer(s).

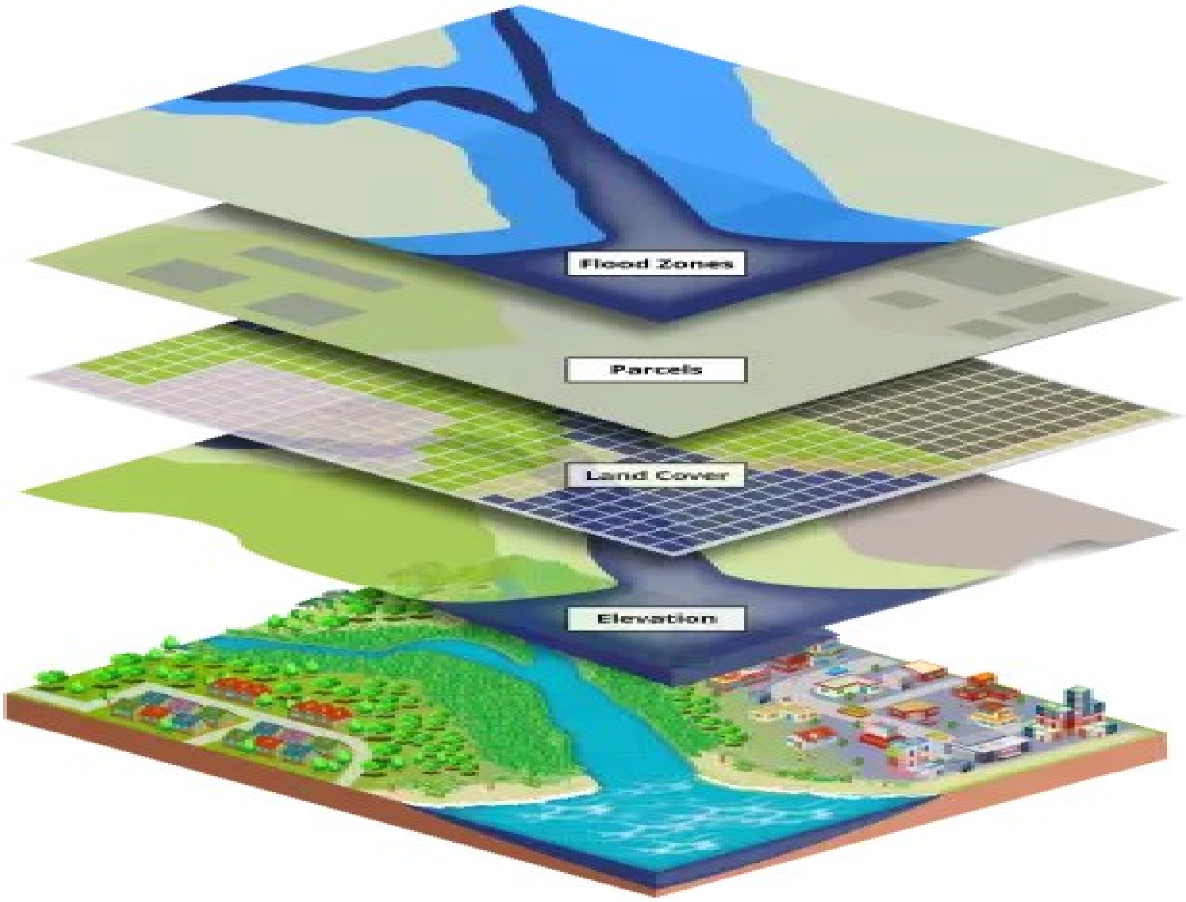

Figure 12: Maps Overlaying in a QGIS (Adapted from [53]**)**

Buffering or Zoning around the 33kV lines capacity and above at 3.5 km and 15km of each resource base was done. These buffer zone distances were used in the design of 2017 electrification master plan. They were kept in the analysis so as to make the results of this project comparable and easily aligned to the master plan results. The distances constitute the minimum (3.5km) and maximum (15km) buffering distances. The resource potential within and outside these buffer zones were determined and the locations wherein the potential could be derived were identified through digitization.

The results given in the study indicated whether it is economic to invest in power generation from a particular place or not. Several factors were examined for each place to be considered viable and suitable for investment. These factors included the renewable potential available in the designated place, the district wherein the place is found, the settlement type of the place, ecological zone, the distance to the grid for power wheeling, road network accessibility, villages around the area, and others.

3.5 Critical Factors to be Considered

Proximity to the existing grid (especially high voltage lines capable of power wheeling), substations, and road networks was considered as one of the major critical factors in prioritizing places for exploiting renewable energy potential for power generation. Land use type will also be strongly considered in selection of viable places. Places where major power generation gets in conflict with food security, the priority areas as set out in NSDPII of the country will take precedence [54]. Arable land that is still intact, rich and productive, may not be used to set-up solar power plant. Land use change is rapidly taking place in Lesotho as people encroach to places designated for other land use such as agricultural production. This places high pressure on the remaining fertile land to produce sufficient food for the growing population of Lesotho.

The cost of building the power generation plant in the selected places will be calculated using the current market prices for construction of power generation plants including operation and maintenance. Finally, the prioritization of power generation places and scheduling will be done.

3.6 Scheduling Optimisation Procedure

The demand of electricity forecasted through log-linear-extrapolation was matched with the generation station determined from the analysis of selected areas. The generation power stations determined from each of the resources present in the selected area, were prioritised according to the cost of generation and accessibility of the place. The accessibility was determined according to the type of road infrastructure present in the area. The ranking was done in excel with the least costly generation stations being taken first in order of preference. The generation stations were added into the generation stream to meet the demand of any period sequentially, that is, by order of cost and ease in accessibility. The attribute analysis of the selected places for generation led to the assessment of investment potential in the area influenced and reflected by the extent of the resource available, existing infrastructure on the ground, terrain and number of villages within the area.

3.7 Costing of Power Stations

The cost of producing energy from each of the renewable energy sources was determined by finding out the current global utility scale of unit production from the specified renewable. A generic costing procedure was followed to come up with estimate plant cost. This implies that it would be prudent at the time of implementation to cross-check if the costs are still applicable and relevant. The cost of renewable technologies is fast declining.

Chapter 4: Results Presentation and Discussions

This chapter presents results obtained from previously done studies on future energy demand of Lesotho. These results were compared to establish the best forecast scenario that suits the socio-economic conditions of the country. The forecasted demand as shown in the methodology from different studies was extrapolated to fill in the missing data in some years in the forecast using excel and presented cognizant of the impact of Covid 19 on socio-economic situation in the country. The aggregated demand from these forecasts formed the basis for envisaged future power demand for Lesotho. Proximity analysis results of the resource base to the grid, primary road infrastructure and substations at 3.5km and 15km buffer zones were presented. Suitable places for energy generation and grid integration were identified and the amount of energy that can be generated from these places was estimated and evaluated.

4.1 Power Demand Projection

The future electrical power demand as depicted in Figure 13 was projected using logarithmic extrapolation in excel to predict what the future demand for energy would look like using the known demand derived from [21], [44], [55]. The extrapolation is from 2022 to 2040. The logarithmic function for the required demand is represented by:

$$Y = 17789\, linx - 135512 \qquad \text{Equation 1.}$$

Where Y represents the peak demand and x is the year in which the demand will occur.

This extrapolation was compared with linear extrapolation and found to be the best fit unlike linear extrapolation that predicted 400MW in 2040. The demand path is unlikely to reach this level given the impacts of Covid 19 on the local and international markets and the time it will take for the economy to recuperate [56], [57]. Logarithmic extrapolation predicted demand to reach about 350MW in 2040 which falls below electrification master plan prediction of about 420MW [55] and Senatla et.al study using ARIMA based forecast which estimated 363MW peak on base scenario for 2035 [21], thus, making this study's projection more favourable to previous stand-alone projections.

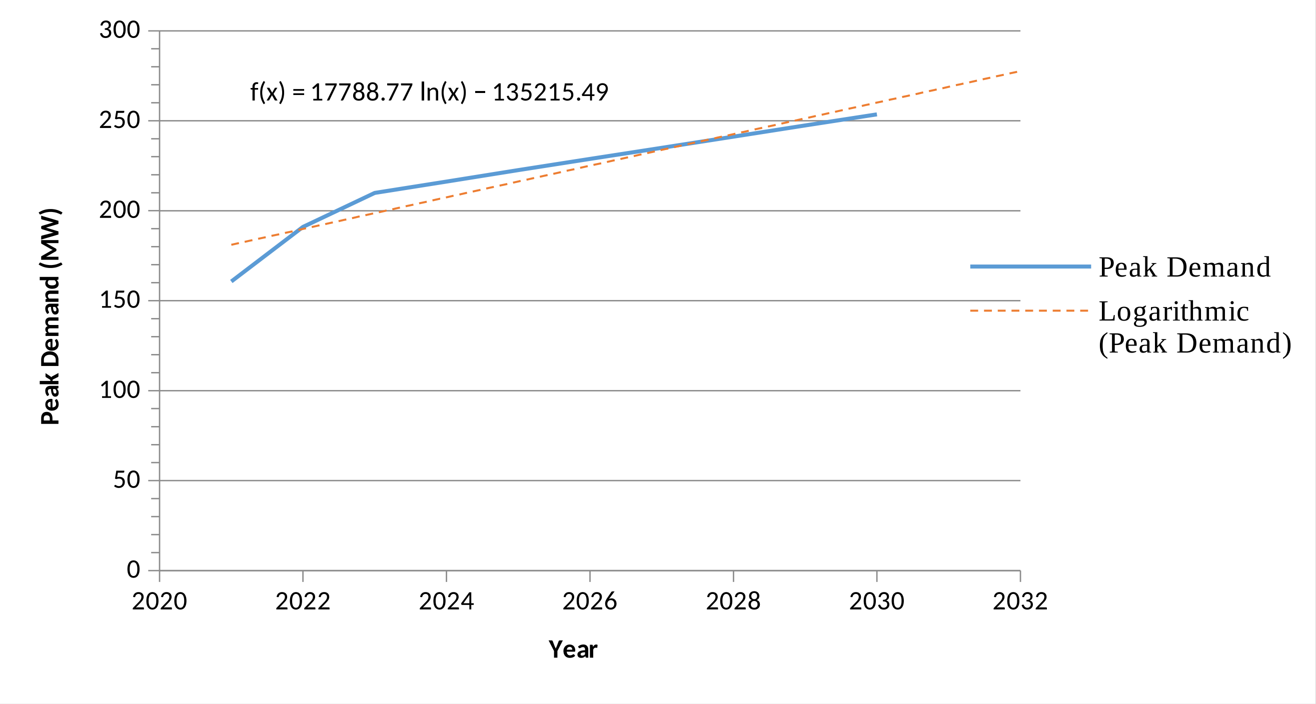

Figure 13: Average forecast electricity demand derived using logarithmic extrapolation

4.2 Renewable Resources Analysis

The renewables available in the country and evaluated in the resource base maps, were spatially analysed using geographic information platform (QGIS) in which buffer zones around LEC grid and the secondary road network were determined in relation to the availability of the resource. The results of this analysis are presented in the maps that appear under this section. The selected and digitized places were identified by eye inspection on the map and legend association. These maps were generated during the analysis of input data into QGIS software used in this research.

4.2.1 Photovoltaic Analysis at 3.5km Buffer

Figure 14 shows Photovoltaic Power Analysis at LEC 3.5km buffer. This map came up as a result of map production exercise and proximity analysis explained in section 3.2 and 3.4 respectively. The LEC network ranging from 33kV to 132kV is shown in gray and black lines within the map whereas the primary road network is depicted in white lines. The range of photovoltaic power accruable to different places is categorized and classified in different colours. The bright yellow indicates where there is a high photovoltaic power whereas the blue colour shows where there is a low extent of the power. Most of the high photovoltaic power can be derived from highlands; that is, along the central range which includes places like ‘Mats’ooana plateau and Thaba-Tseka. Thaba-Putsoa range (Ha Mohale to Semonkong) and Maloti range, especially in places like Mphosong and ‘Moteng, also showed a high level of PV power. Most of these places are remote and difficult to access but those within the 3.5km buffer of LEC grid can be exploited.

However, it can be observed from the map that the country has photovoltaic power potential ranging from 2164 kWh/kWp to 2249kWh/kWp even around LEC power lines. The unit kWh/kWp refers to the amount of electrical energy that can be produced. It is the ideal array yield according to the rated power output (P_{rated}). This potential is quite agreeable with what the existing literature asserts that Lesotho is richly endowed with solar power [17]. This study is however different because it seeks to point out where such potential exists in terms of location. The challenge that remains is coming up with mechanisms to exploit this great potential in these locations such as designing a cost effective IRP for the country.

In , places that are rich in the solar resource and close to the 3.5km buffer have been identified and digitized as site 1 to site 7. The average amount of solar energy that can be produced in these places and the area of each is shown in Table 6. The buffer is a zone that is drawn around any point, line, or polygon that encompasses all of the area within a specified distance of the feature such as LEC electricity grid and road network in this study. It is intended to make the results of the study comparable to the electrification master plan.

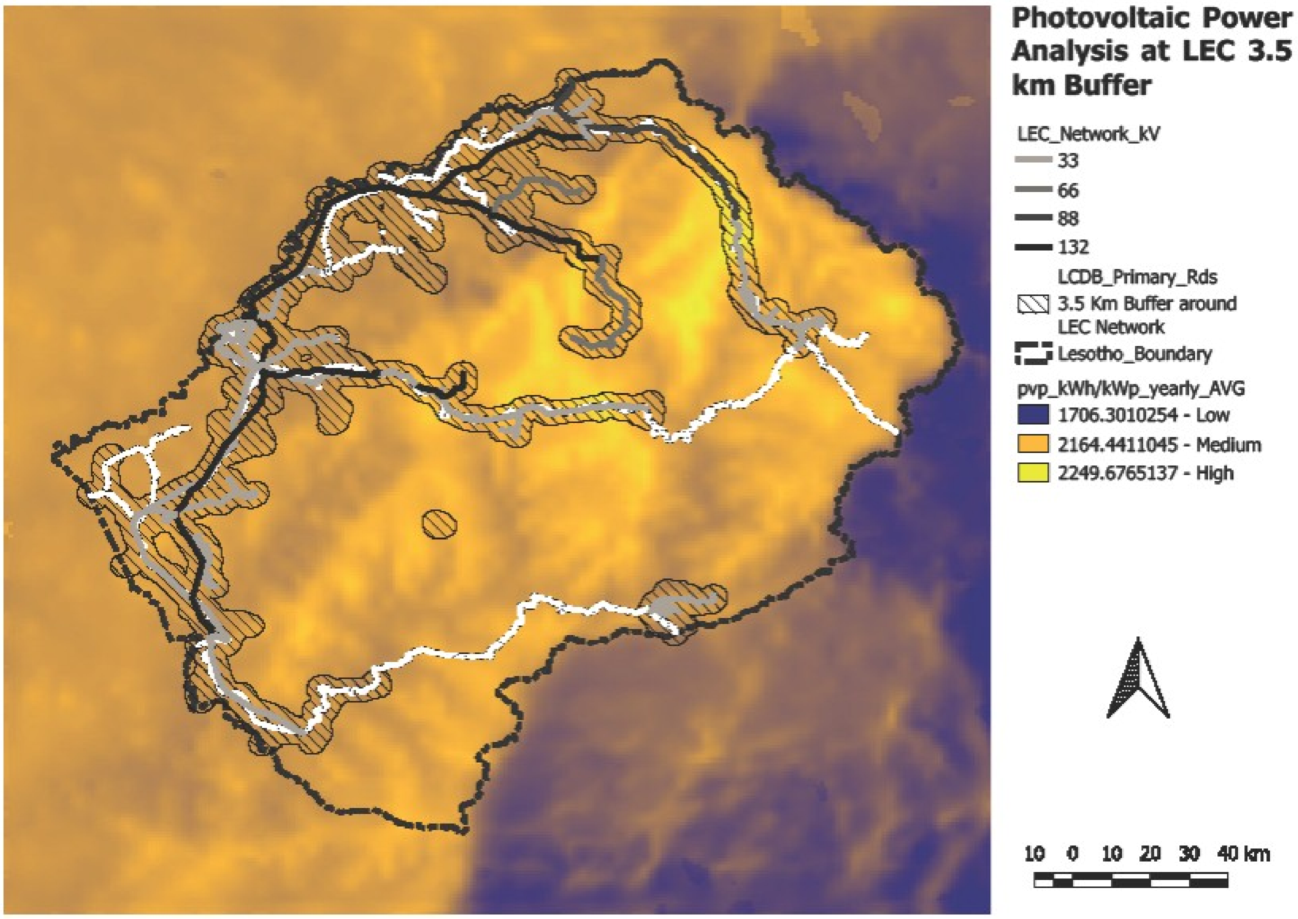

Figure 14: Photovoltaic Power Analysis at LEC 3.5km buffer

.

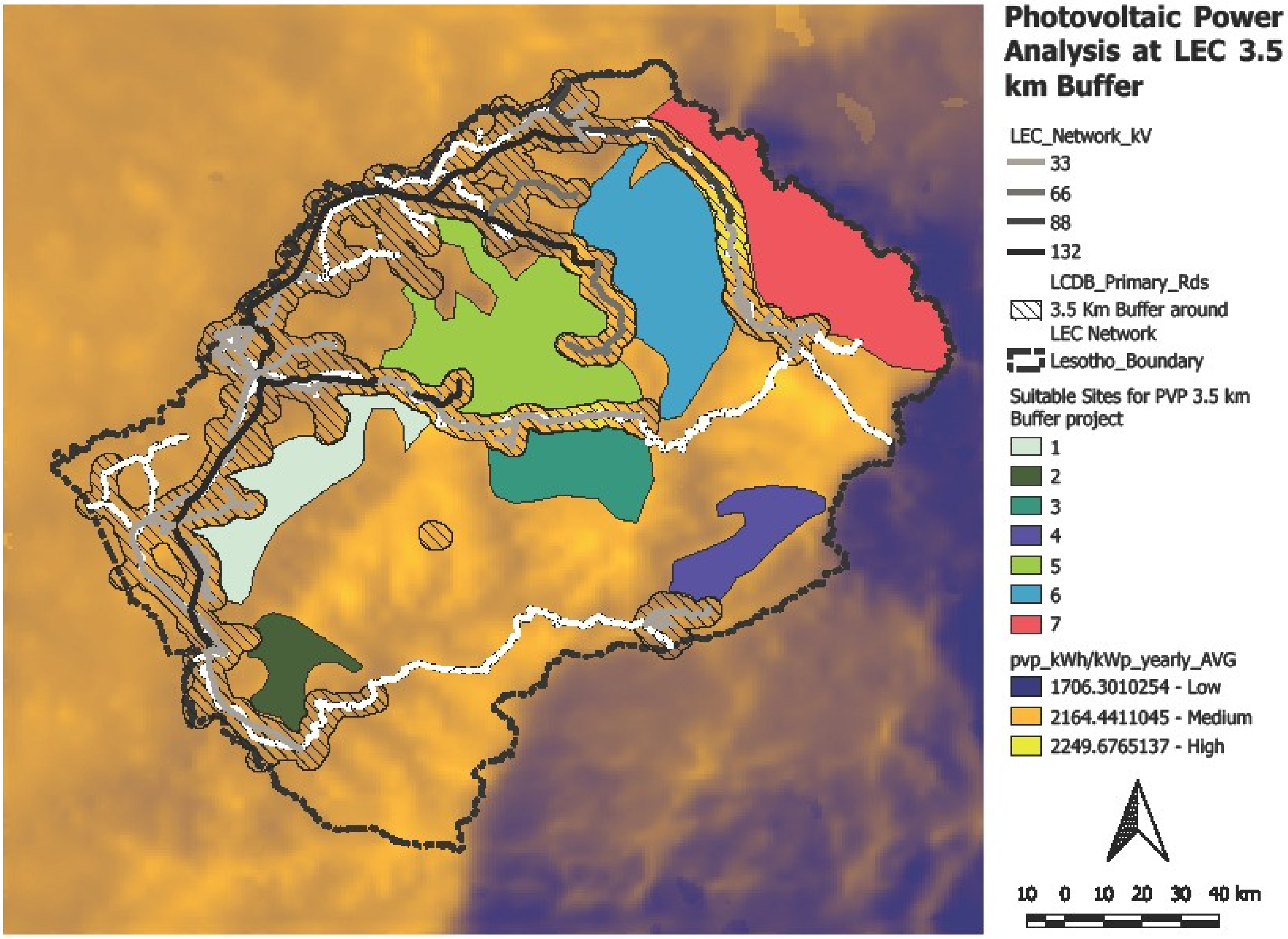

Figure 15: Photovoltaic power analysis at LEC 3.5Km with selected suitable places

The selected area and yearly average of Photovoltaic Power Available at 3.5km buffer analysis is indicated in Table 6. The largest area endowed with much photovoltaic power was site 7 with a corresponding yearly average kilowatts peak of 2164.44, followed by site 5 and 6 both with yearly average kilowatts peak of 2249.68. The least digitalized area was site 2 corresponding to 2249.68 yearly average kilowatts peak. The Coordinates of the selected places have been indicated to facilitate spatial identification of the selected sites. The selected site identification number is not in any order of precedence. It was arbitrarily placed to facilitate ease in analysis and targeting.

The selected area 7 in Table 6 presents a good opportunity for investment in PV power generation since it is nearer mining areas such as Lets'eng Mine which is one of the biggest open mines in Lesotho. Mines consume a considerable amount of energy in a continual basis for their operations. In 2017/18 and 2018/19 years, the mining sector consumed 27,288.08MWh and 28,191.31MWh respectively both equivalent to 5.2 percent of the national consumption [58]. This implies that energy produced in this area may either be fed directly to the mine or into the grid to power nearby villages that is, Mokhotlong town or Lesotho Highlands Water Project at Polihali. The excess can always be exported and sold to South Africa (SA) or Southern Africa Power Pool (SAPP).

Table 6: Selected Area and Yearly Average Photovoltaic Power Available at 3.5km buffer

Selected site identification	Energy (kWh/kWp yearly average)	Coordinates	Area (m²)
1	2164.44	27.68175,-29.67851	938309496.18
2	2249.68	27.64471,-30.16752	455320898.17
3	2249.68	28.43868,-29.63946	826876196.36
4	2164.44	28.91620,-29.83903	605061708.54
5	2249.68	28.24428,-29.31642	1883308654.66
6	2249.68	28.66122,-29.10737	1748606142.45
7	2164.44	29.07012,-29.07980	2032448047.33

Shows Selected area attributes for photovoltaic power at 3.5km buffer. These area attributes were observed using Google Earth application. The digitized map depicted in

was changed to KML format suitable for Google Earth analysis. The changed format was then placed into the Google Earth analysis window and the application immediately zoomed into the digitized area. The bird-eye view analysis was done in all places to determine what features existed, hence the respective attributes of each area. This analysis informed the type of power generation stations and their estimated power generation capacity that could be implemented in the specified area.

Some key variables that were considered to inform the size of a PV plant at utility level that could be implemented in an selected area were: the size of the selected area, the extent of agricultural activities within the selected area, the accessibility of the place through road network, the terrain as well as number of villages within the selected area. The utility scale power generation requires a sizeable free land with minimum obstructions, no shading and favourable temperature conditions.

Table 7: Selected area attributes for photovoltaic power at 3.5km buffer

Selected Area	Selected Area Attributes
1	This area borders Mafeteng and Maseru and has the following villages: Ha Raleqheka, Moits'upeli, Ha Nako, Nkesi, Malealea, Kena, Motanyane, Matsaba, Matelile, Ramosoeu, Thabaneng and Helehehle. These villages have a sizeable population of households. A large area of arable land can be identified around Matelile. A tarred road is available and several gravel in-roads to the villages. There is also Makhaleng river passing through this area.
2	There are rivers existing in this area, mainly the Orange river and Qaqatu river. It is mostly a cattle posts area. A gravel road is found in this area. The settlements are very much far apart from each other with few patches of fields.
3	This area is mainly found in ThabaTseka district. A good gravel road exists in this area. Several concentrated villages can be found with primary schools. The place is mainly mountainous yet reachable.
4	This area seems to be difficult to reach with many high mountains rising from every side. A number of cattle posts areas were observed and villages such as Melikane, Ha Libete, Ha Sefaha and Ha leqooa. There were two rivers observed, Leqooa and Qulu flowing through this place. No clear access road was identified.
5	These area touches the borders of several districts; ThabaTseka, Berea, Leribe and Maseru. A number of rivers and streams are found in this area. There are Phuthiatsana river, Senqunyane, Bokong and Bokoaneng rivers running through this area. There is a gravel road network linking these area with others outside the boundary. Scattered fields are present in some places further afield from each other.
6	This area has the following villages that were observed through google Earth: Rakotoane, Motete, and Laoti. There were cultivated fields around the villages. At Motete, a High School was found. Steep hills and high mountains adorn the area on every side. The Matsoku and Malibamatso rivers pass through this area.
7	Many villages were found in this area and Letseng Mine. Gravel roads are used to access these villages. There was Morimoholo river along whose banks there were several fields that seemed cultivated.

4.2.2 Solar Farm Costing at 3.5km Buffer

The suitable areas were selected using multiple criteria procedure to estimate the size of a solar farm (utility level) that could be constructed. The attributes in each suitable area constituted major factors in the selection procedure for an area to be viable for PV generation and were also determinant factors in the size of the plants. The solar farms indicated in Table 8 are examples of estimate power plants for each suitable area over the period of the study. The solar plant cost for producing 1 MW of energy at utility level was used to calculate the total cost of the estimated system for Area 1 only. This was an average cost since the range of building this size of plant was estimated to be $800,000 to $1.3Million [59]. The cost of other solar farms to be built in the future and installed was derived based on the future projections of solar energy as indicated in Table 1. The cost of HV-line was adapted from electrification master plan [55]. It is the cost of constructing 33kV 3-phase line per km. In the places where the access roads were not conspicuously there nor upgraded, the distance to the next substation was longer. All these areas are found in mountainous regions which are very difficult to reach. Although these areas demand a high level of investment to pitch a power station, it is anticipated that the returns on investment can be realized quickly from them.

Table 8: Cost of solar farms in different suitable areas

Suitable Area	**Type of Plant**	**Solar plant cost (USD/MW)**	**Plant Capacity (MW)**	**HV line length-Substation (km)**	**Cost of HV line (M/km)**	**HV line Total Cost (USD)**	**Total Plant cost (USD)**	**Estimate System Cost (USD)**
1	Solar Farm	1,000,000	30	4	386,760	93,760	30,000,000	30,093,760
2	Solar Farm	834,000	20	5	386,760	117,200	16,680,000	16,797,200
3	Solar Farm	834,000	15	6	386,760	140,640	12,510,000	12,650,640
4	Solar Farm	834,000	20	7	386,760	164,080	16,680,000	16,844,080
5	Solar Farm	587,000	25	3.5	386,760	82,040	14,675,000	14,757,040
6	Solar Farm	481,000	40	15	386,760	351,600	19,240,000	19,591,600
7	Solar Farm	587,000	30	5	386,760	117,200	17,610,000	17,727,200

4.2.3 Photovoltaic Analysis at 15km Buffer

Figure 16 illustrates photovoltaic power on panel analysis at LEC 15km buffer. The places within 15km buffer around the LEC network that indicates a higher degree of photovoltaic power potential on plane are mostly in the mountains ecological zone. A large area of regions falling within the 15km with photovoltaic power on panel ranging from 2164.44 to 2249.67 annual average PV yield is observable in Thaba Tseka, Central range and Thaba Putsoa range. Other areas outside the 15km buffer zone depicting high and medium photovoltaic power have been digitized and their area evaluated as indicated in Figure 17.

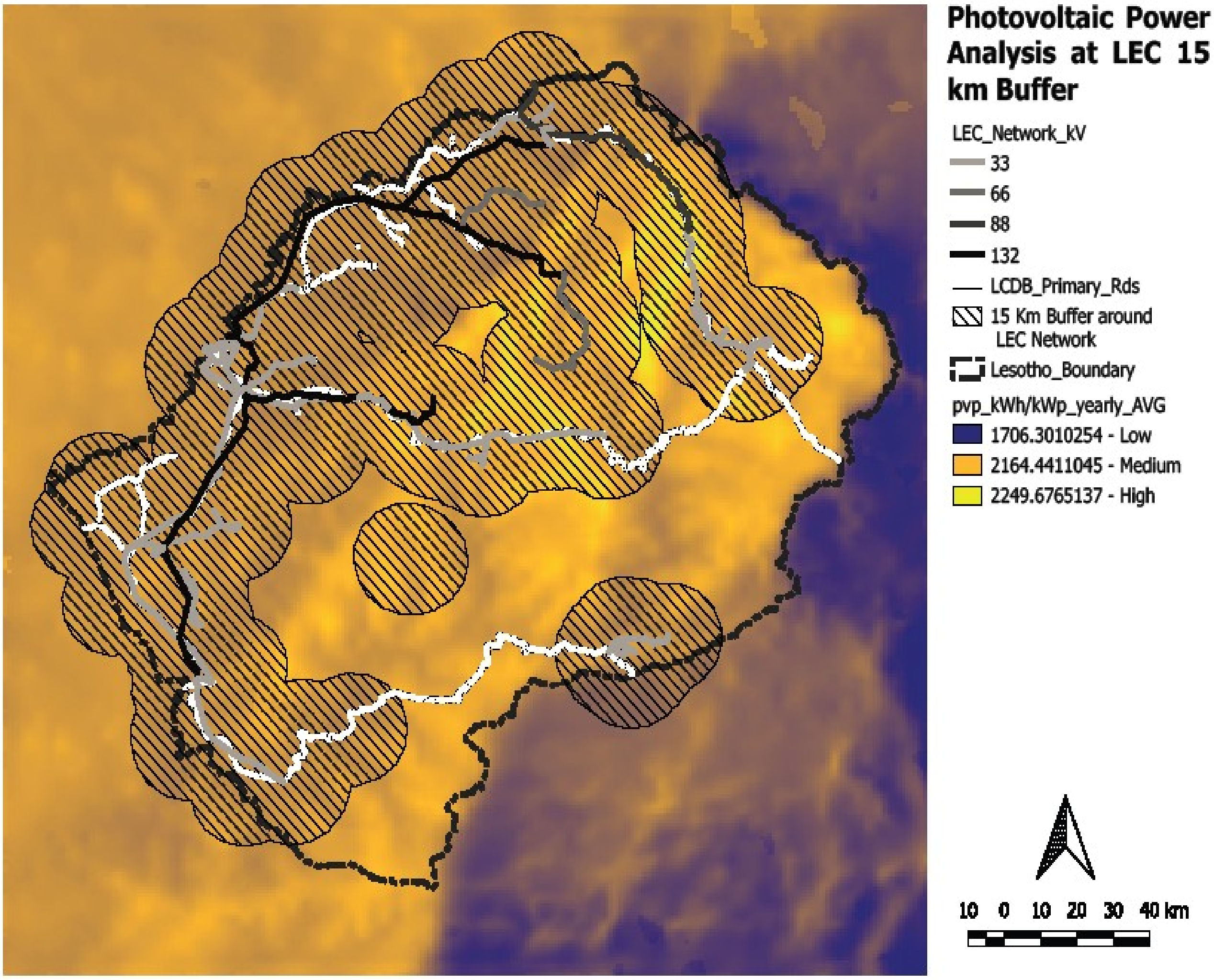

Figure 16: Photovoltaic Power on Panel Analysis at LEC 15km Buffer

The map depicting photovoltaic power on panel analysis similar to the one shown in Figure 16 but with selected suitable sites for PV energy production is presented in Figure 17. There are seven suitable sites that could be utilized in producing PV energy digitized around the 15km buffer like in 3.5km analysis. The sites have different degrees of annual average PV yield (kWh/KWp) as shown in Figure 17.The magnitude of the difference between medium and high PV yield is 85.23 constituting 3.8 percent. The percentage difference is minimal in magnitude thus suggesting all places with medium or high PV yield can be selected indiscriminately for investment in energy production. It should be noted that generally the 15km buffer zone covers most of the places digitized and evaluated under 3.5km buffer zoning. This implied that the analysis on estimation of power stations at this level be not considered since they will be well represented under 3.5km buffer zone. It is however necessary that this zoning be done to reveal if whether there exist any places outside the zone endowed with rich renewable resources. Though it will be expensive to reach these places, but they are feasible in terms of renewable energy investment.

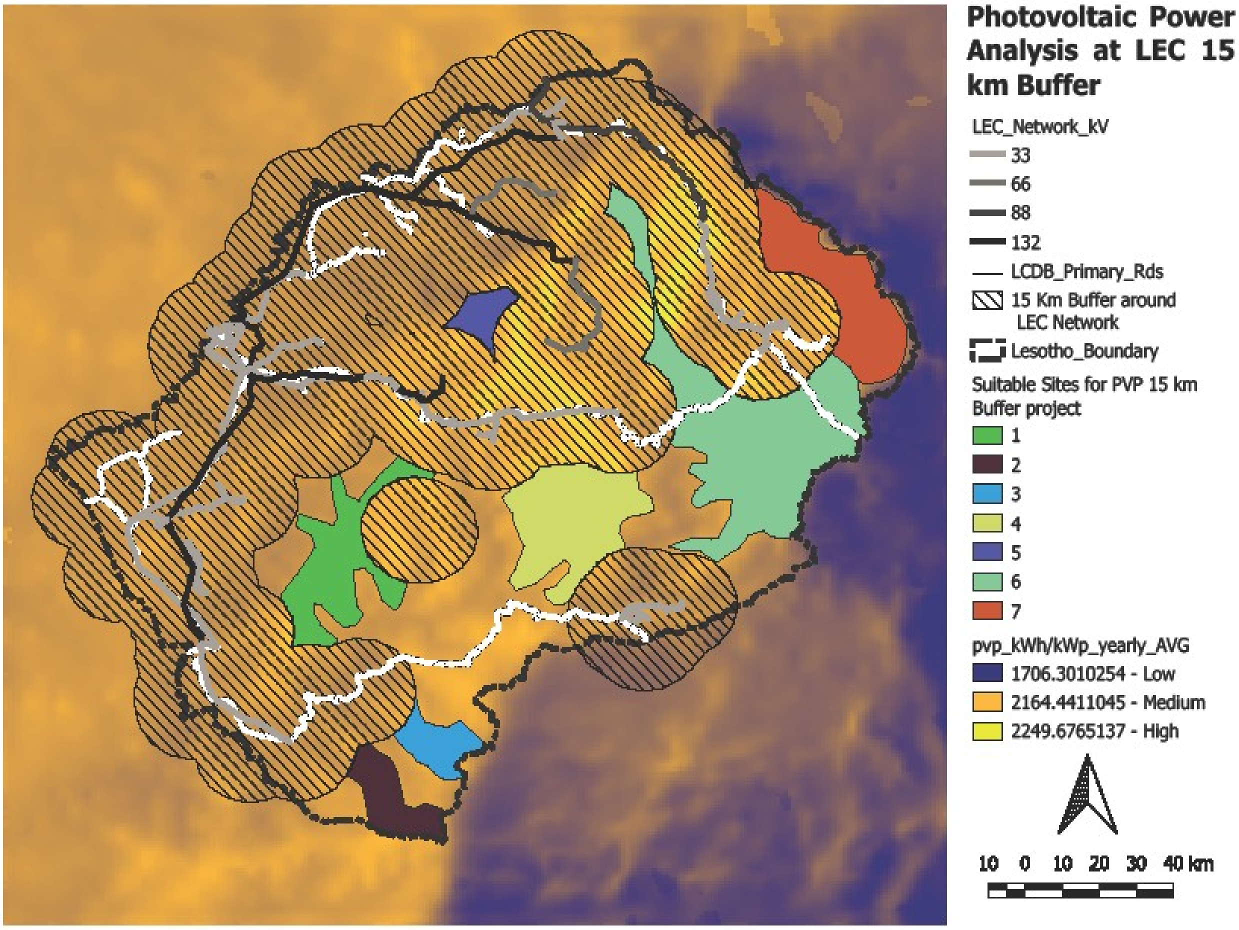

Figure 17: Photovoltaic Power Analysis at LEC 15km buffer with Selected Places

The higher the kWh/kWp number, the more the energy will be produced from an installed module in the specific site. This unit is intended to include real-world fluctuations as opposed to kWh/m^2 which only captures the amount of energy a surface receives during sunshine. Table 9 shows selected sites, annual yearly average of photovoltaic power and area (m2) at 15km buffer. The selected identification number tallies with the site number indicated in Figure 17. Site 6 with 2164.44 yearly average kilowatt peak has the greatest area for photovoltaic power derivation followed by site 4 and site 7 both with 2249.68 yearly average kilowatts peak.

Table 9: Selected sites, Annual Yearly Average of Photovoltaic Power and Area (m2) at 15km buffer

Selected site identification	kWh/kWp yearly average	Coordinates	Area (m²)
1	2249.68	27.80875,-29.90615	793603454.59
2	2249.68	27.95612,-30.54777	357626447.79
3	2249.68	28.09200,-30.40697	268095996.74
4	2249.68	28.48056,-29.79150	1014873536.37
5	2249.68	28.22731,-29.24580	174736698.67
6	2164.44	28.95145,-29.56591	2171120032.48
7	2249.68	29.26471,-29.16738	927209440.57

4.2.4 Global Irradiation on Panel analysis

Global Irradiation on Panel was analyzed around LEC grid at 3.5km buffer as shown in The secondary road infrastructure was overlaid on the irradiation map to evaluate accessibility to places where there is a higher degree of the solar irradiation. The places where the irradiation was identified to be high (About 2269kWh/m^2) and within reach from 3.5km buffer were digitized as depicted in Figure 19. Furthermore, the estimated amount of energy that could be derived from these places have been evaluated in Table 10. The estimation was not done with consideration of the ground terrain. It therefore means the estimated value must be used with caution since it generally covers the digitized area. It is however useful to have these values since they are based on the observed value of the global irradiation from the given maps.

The country generally has high to medium global irradiation on panel (GIP) with 2188.27 and 2268.91 kWh/m^2 respectively, as depicted in . There are few places where the GIP is low (1754.85kWh/m^2) and these places are mostly located on the eastern part of the Thaba Putsoa range and central range. Most global irradiation can be derived from high altitude places in the mountain areas of Lesotho. Also, these places are mostly the less electrified by the national utility due to sparsely distributed population of the rural areas. On the other hand, a lot of free land in the mountains which is generally used for grazing, provides an ample opportunity for investment in renewable energy.

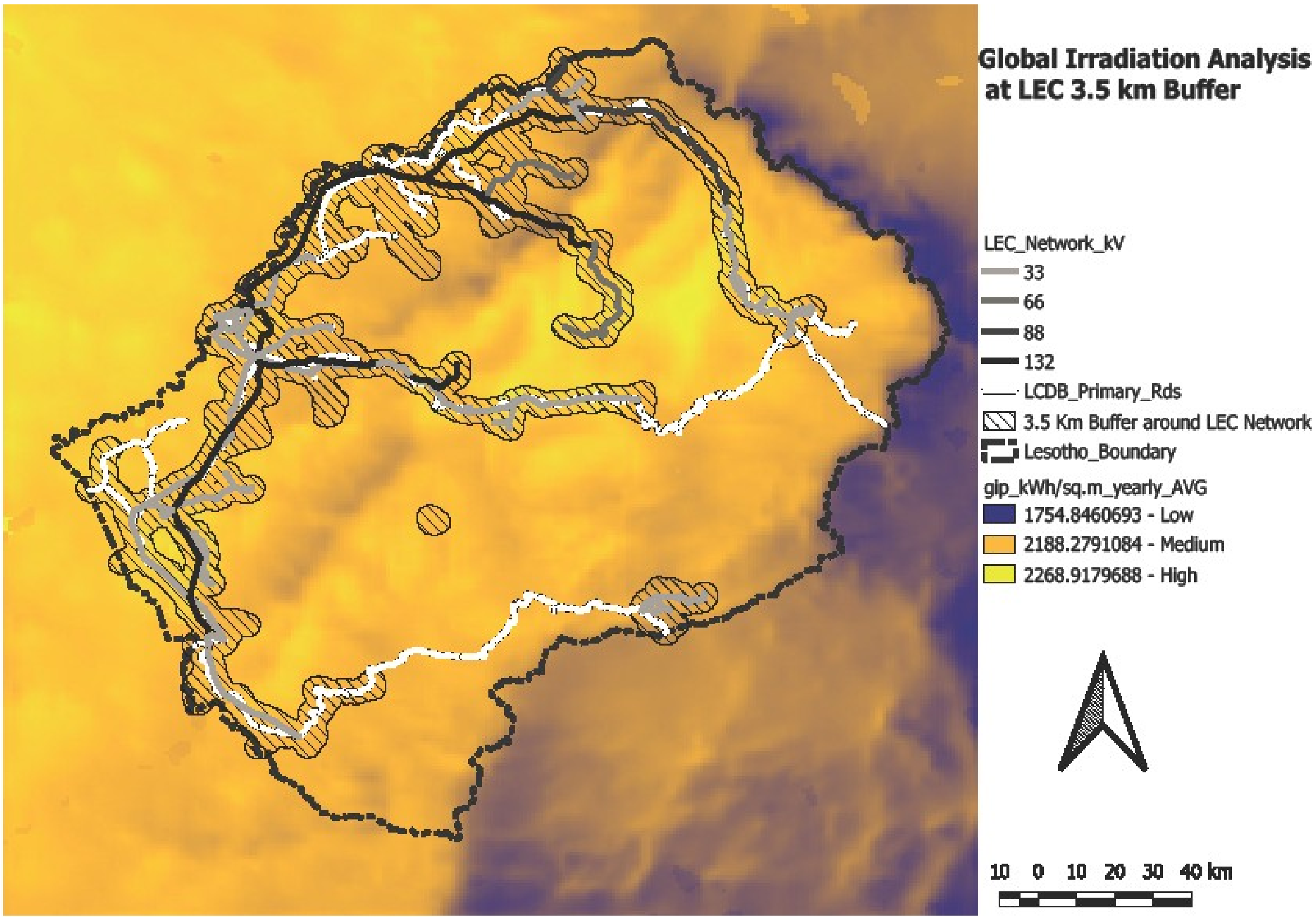

Figure 18: Global Irradiation Map at 3.5km Buffer LEC Grid

There are 11 suitable sites for global irradiation on panel identified at 3.5km buffer analysis shown in Figure 19. These places are close to the primary road network and LEC network (33kV-132kV) and can be capitalized upon to produce the needed energy which will help close the energy deficit already experienced in the country. These sites were prioritized since they have medium (2188.27) to high (2268.91) global irradiation on panel yearly average. This level of irradiation presents a good possibility of returns to investment since more solar energy can be produced annually. The places are found in different districts such as Mokhotlong (Lets’eng area), Leribe (Maluti range), Berea (Maluti range), Mafeteng (Ts’akholo) and in southern part of Mohale’s hoek (Awynskop).

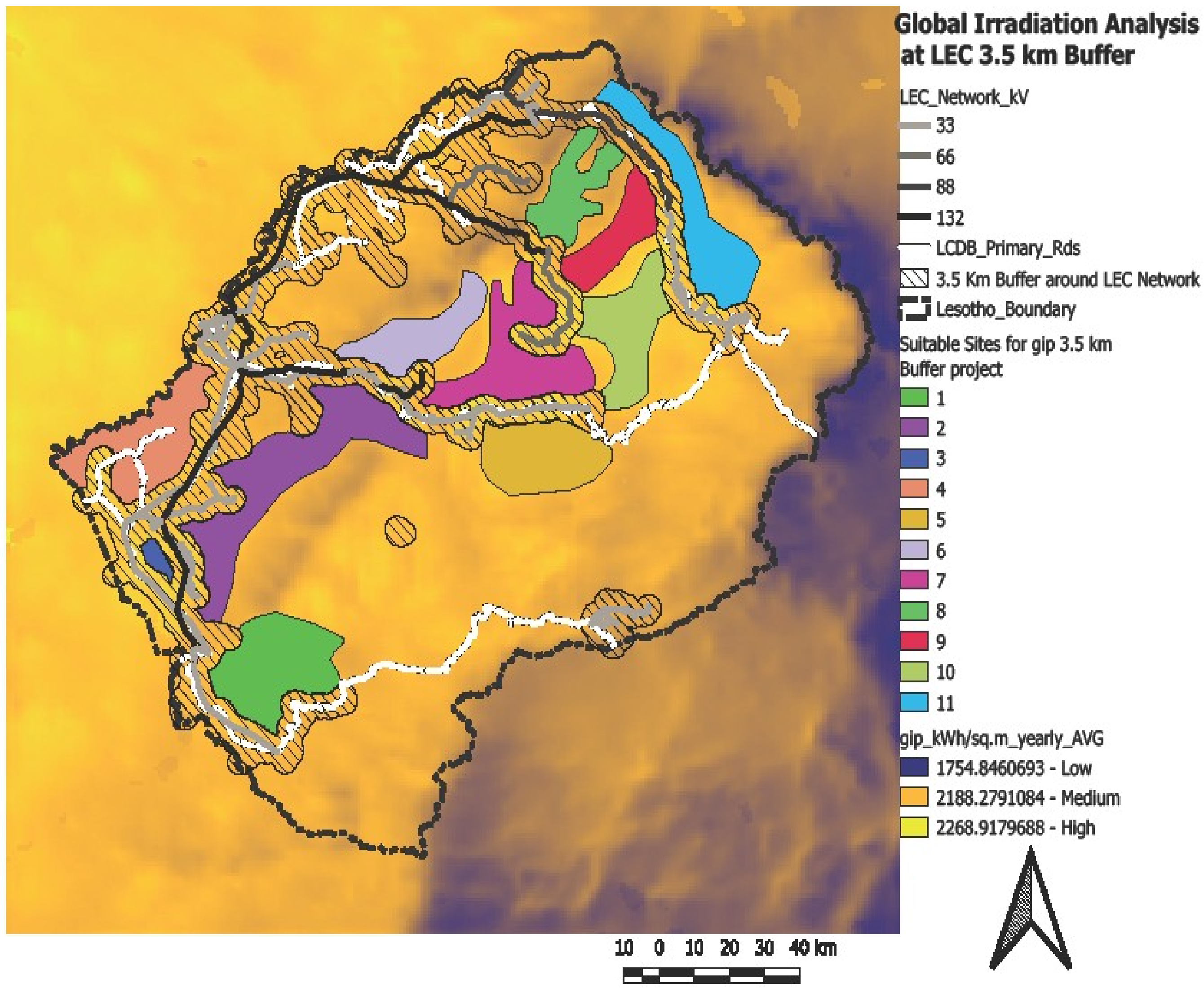

Figure 19: Global Irradiation Analysis at LEC 3.5km Buffer

The attributes and potential energy that can be produced from the selected suitable sites illustrated by Figure 19 are shown in Table 10. Further in-depth analysis of the terrain of the places is done in Table 11. The greatest potential of solar energy calculated from the global irradiation on panel values at 3.5km buffer for Lesotho can be found in site 2 (2,633,806.41GWh) followed by site 1 and site 4 with 1,801,701.22GWh and 1,752,160.07GWh potential respectively. Site 2 is easily accessible with good gravel road as shown in Table 11 and can be prioritized for renewable energy production. This site also demonstrates abundance of solar energy resources in the PV resource analysis at 3.5km buffer zone. Site 1 is far in the mountains whereas site 4 is in the lowlands. Generally, selected sites that are in the lowlands are easy to access and lend cheaper costs of establishing a generation plant than the sites in other ecological zones. Priority should be placed on such sites. The least derivable energy is recorded in site 8 (966,563.05GWh) which has Motete village, site 9 (872,494.21GWh) in Matsoku and site 3(125,729GWh) which did not show any village. The coordinates of the selected sites serve as identifiers of the places. The corresponding area and the potential derivable energy were also estimated.

Table 10: Selected sites, Area (m2) and Potential Energy Production due to Global Irradiation on Panel at 3.5km buffer.

Selected site identification	(GIP) yearly average (kWh/m^2)	Coordinates (S,E)	Area (m^2)	Potential energy production (GWh)
1	2268.92	27.66510,-30.17987	794079487.22	1801701.22
2	2268.92	27.69726,-29.65841	1160820462.52	2633806.41
3	2268.92	27.32030,-29.89796	55413882.76	125729.55
4	2268.92	27.30695,-29.59717	772244783.44	1752160.07
5	2268.92	28.46014,-29.63508	648173177.23	1470651.77
6	2268.92	28.12016,-29.33070	485664810.73	1101933.62
7	2268.92	28.37055,-29.40076	785890824.46	1783121.81
8	2268.92	28.54284,-28.95741	426001760.38	966563.05
9	2268.92	28.70709,-29.06882	384541979.65	872494.21
10	2268.92	28.73006,-29.30084	598055748.72	1356939.43
11	2188.28	28.92302,-28.97808	704621274.46	1541908.01

Table 11: Attributes of Selected Sites with high Global Irradiation on Panel at 3.5km buffer

Selected Area	Selected Area Attributes
1	Bird eye-view selected place analysis through Google Earth revealed the following features: Scattered fields, Ketane High School and Primary School, large area of cattle posts, some dry streams and Maphutseng river. Generally hard to reach terrain.
2	Google Earth bird eye-view Analysis showed good access gravel roads to Maqoala village, Makoali and Makhaleng rivers meandering through the area, large flat plains uncultivated and scattered settlements (villages)
3	In this area, the terrain is flat and easily accessible, there are good gravel roads to access the villages, and many fallow fields were spotted as well as a primary school and a large extent of desert place.
4	The following villages were identified by Google Earth when viewing this area; Ha Mabotse, Ha Chere, Mapotu, Ranko, Tholo, Petlane, Kolo, Malimong, Reisi and Ha Sekoala. It runs along Mohokare river, little to no vegetation was observed in most areas.
5	This area consists of a vast mountainous area, fertile loam soil fields, a gravel made access road and a river (Lesobeng) running through. Most of the place is hard to reach
6	The place is very much accessible with a gravel road constructed touching a number of villages within a close proximity to each other. There is also a clinic observed within this place. Again, Ha Rapokolana high altitude

	training centre is found in this area. There are few fields observed that have been cultivated.
7	In this area, we have Bokong river, horse tracks and Katse dam. A number of scattered villages could be seen with gravel road used to access them.
8	The Maliba-matso river which is the main river that serves Katse dam runs through this area. A lot of fields exist along the banks of the river. There is also Motete village which has a High school and a gravel road.
9	Small, easily accessible hills and a gravel road are available in this place. A number of fields that were mostly planted were found in this area. Matsoku river runs through the area and there are sizeable villages as well.
10	The area touches both ThabaTseka and Mokhotlong districts. There is a tarred road in the area. Khubelu village and other villages with interspersed fields were identified. There is larger area that is mountainous and hard to reach.
11	A hard to reach mountainous area with a gravel road. A number of streams are observable serving as tributary to Khubelu river.

4.2.5 Global Irradiation Analysis at 15km Buffer

portrays global Irradiation Analysis at 15km Buffer around LEC grid network (33kV-132kV) and primary road network. A few distances of the primary road network fall outside the 15km buffer zone. These places are observed between Quthing and Qacha’s Nek, Thaba-Tseka and Mokhotlong districts and within Mokhotlong. The figure further indicates that most of the high global irradiation on panel (2268.91kWh/m^2) derivable in Lesotho can be found within this buffer zone.

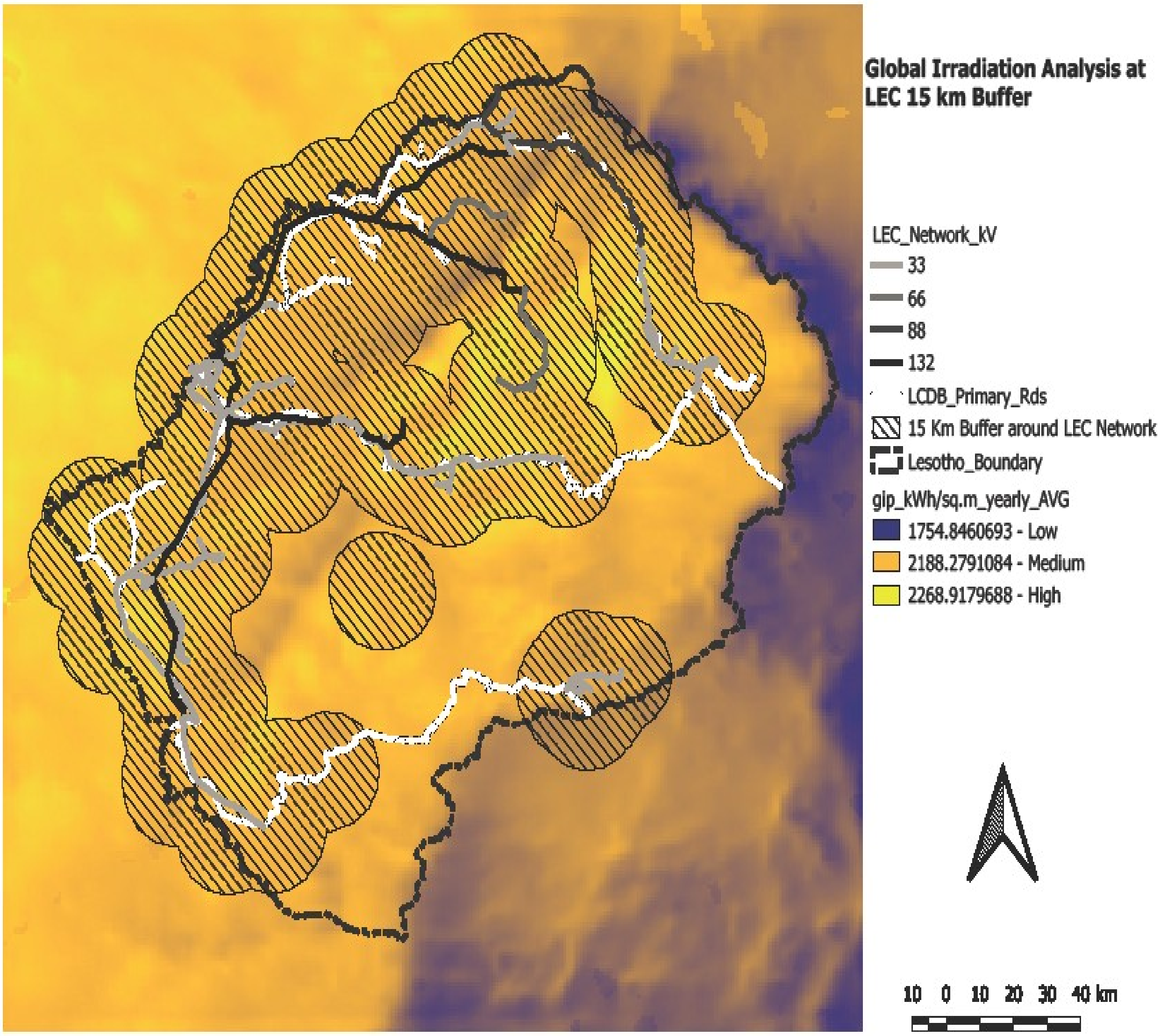

Figure 20: Global Irradiation Analysis at 15km Buffer

There are few dispersed places outside the 15km buffer zone where the GIP is medium to high in degree as shown in Figure 21. There are eight places identified with 2188.29 to 2268.92kWh/m^2 global irradiation on panel. They have been designated suitable places for GIP 15km buffer project in the map legend. The estimated amount of solar energy potential that can be derived from these places is calculated and presented in .

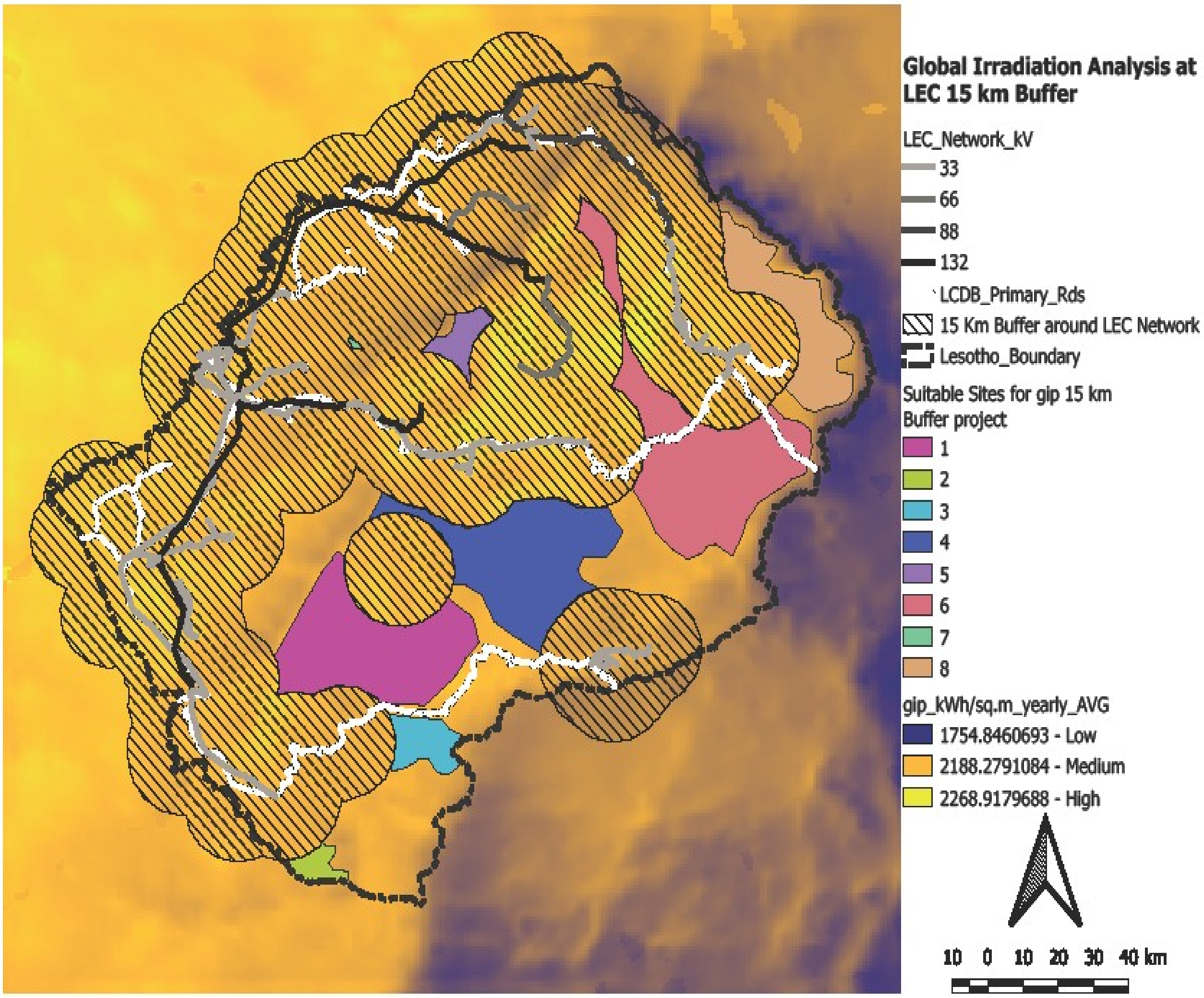

Figure 21: Global Irradiation Analysis at LEC 15km Buffer and Selected Places

presents the selected sites, Area (m^2) and estimated potential energy production due to global irradiation on panel at 15km buffer. The three selected sites with highest potential solar energy production are site 6, 4 and 1 with possible 3,997,903.86GWh, 2,986,379.77GWh and 2,986,259.41GWh per annum respectively. The least solar energy production where the global irradiation on panel is incident can be derived from site 7 with 14235.76GWh. The global irradiation on panel for all selected places was aggregated and calculated to be 1754.84kWh/m^2 (Low), 2188.28kWh/m^2 (Medium) and 2268.92kWh/m^2 (High) during map production. However, the suitable place selection was only on those places that have medium to high GIP.

Table 12: Selected site, Area (m^2) and Potential energy production due to global irradiation on panel at 15km buffer

Selected site identification	GIP yearly average (kWh/m^2)	Coordinates (S,E)	Area (m²)	Potential Solar Energy production (GWh)
1	2268.92	27.965953-30.029722	1316160148	2986259.41
2	2188.28	27.808445-30.577868	108664038	237787.24
3	2188.28	28.125572-30.270102	238067356	520957.82
4	2268.92	28.421446-29.807672	1316213195	2986379.77
5	2268.92	28.235928-29.258614	162842280.3	369475.78
6	2268.92	28.931015-29.52104	1762031027	3997903.86
7	2188.28	27.92018-29.271859	6505460.497	14235.76
8	2188.28	29.215859-29.203706	760518132	1664225.94

4.2.5 Wind Analysis

This section deals with analysis of country wind profile at different buffer zones, possible wind energy production from selected suitable places and analysis of wind and proximity analysis to LEC network and secondary road network.

4.2.5.1 Wind Analysis at 3.5km Buffer

The wind resource base map was overlaid with LEC network map ranging from 33kV to 132kV lines at 3.5km buffer to generate . These lines were specifically selected because they have sufficient capacity to ferry generated power immediately from generation station to distribution line network. The primary road network was also included in the analysis to assess the degree of accessibility of the resource in relation to the indicated proximity radius. The places that appear blue have a very low average yearly wind speed at 200m height with a minimum value of 2.8 m/s followed by yellow coloured places with 9.96m/s and 11.10m/s indicating both medium and high level of wind speeds respectively. There are about 8 places identified which were outside but very close to the 3.5km buffer zone as shown in Figure 23.

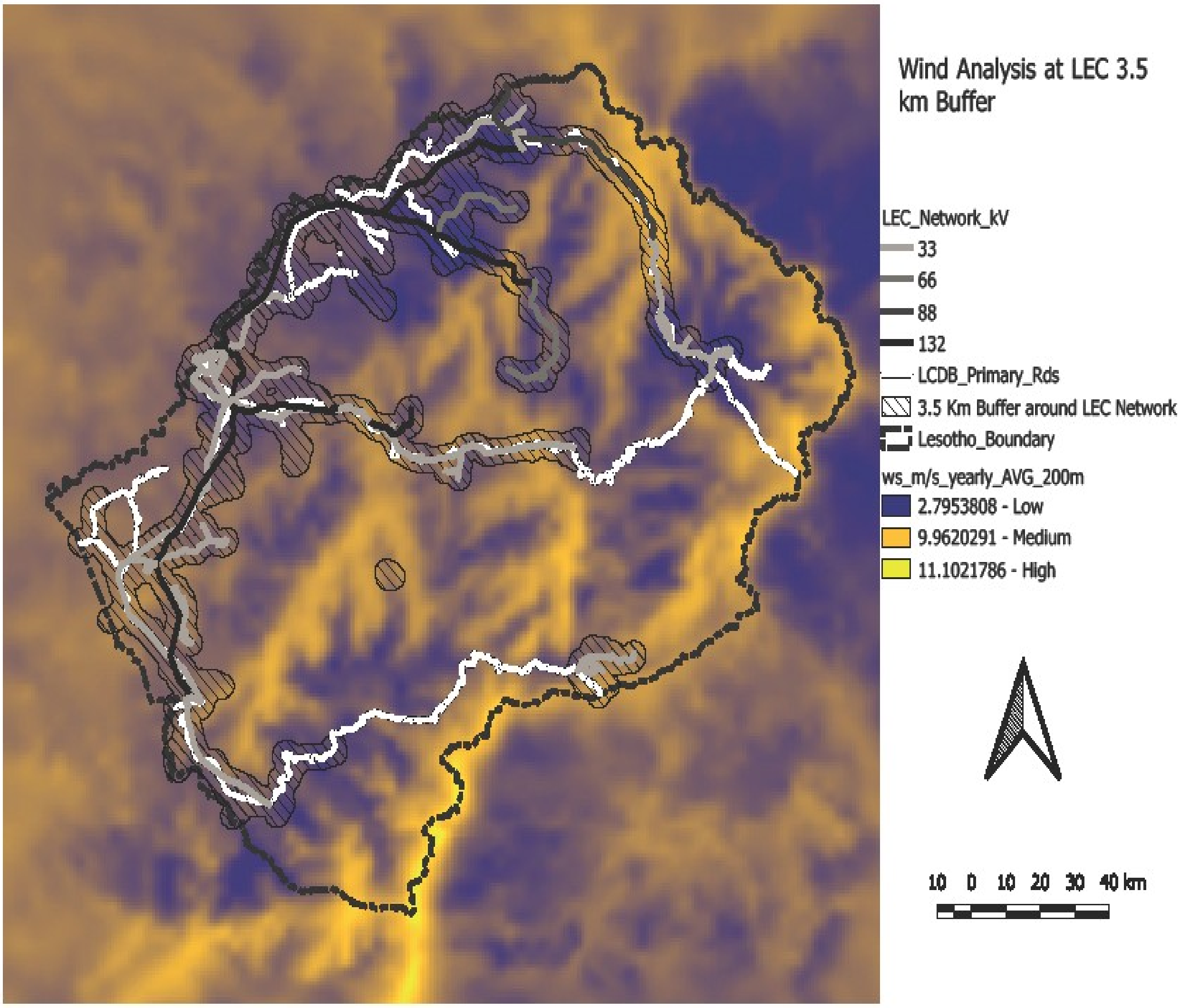

Figure 22: Wind analysis at LEC 3.5km buffer to grid

The map shown in Figure 23 depicts a wind resource base analysis within the proximity of 3.5km of LEC electricity network of 33kV to 134kV. Suitable places wherein wind energy can be generated have been identified through digitization and are labelled from 1 to 8 in the map legend. The labelling is mainly for cartographic identification. Most of the wind speeds with high wind power density can be found in these places. The wind speeds are found to exceed 9.96m/s yearly average at 200m height in these areas. This corresponds to about 650 W/m2 of annual wind potential density that can be derived as indicated in Figure 9. The sites are not very far removed from 3.5km zone hence making the resource within reasonable reach for any investment. It can be observed in site 2 for example, that even though the site is outside the buffer zone, much of the resource is also within the zone and is very close to the primary road network.

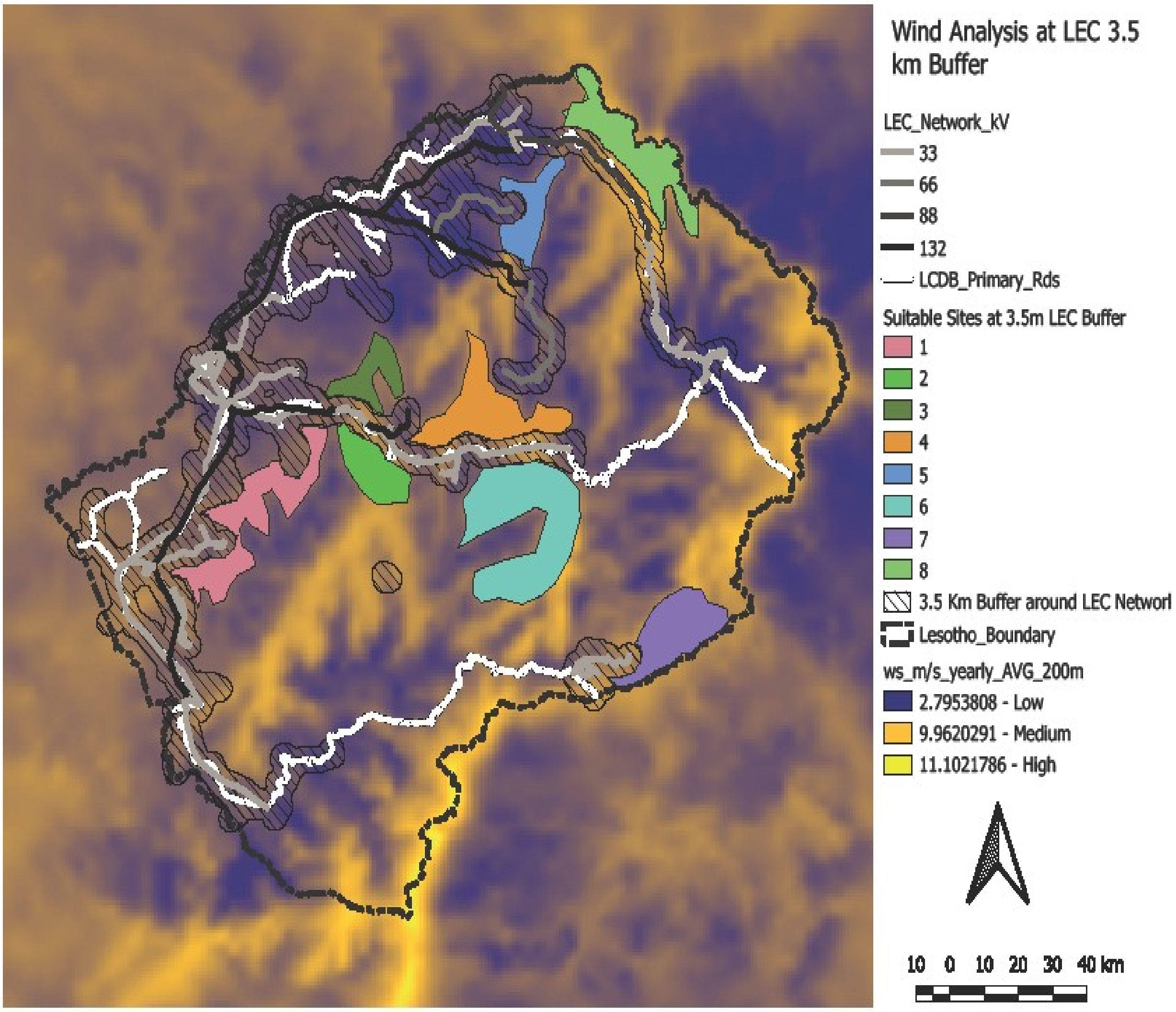

Figure 23: Wind Analysis at LEC 3.5km Buffer

Much of the wind resource potential was observed in high places, such as the Central range, Thaba Putsoa range, Maloti range and along the Drakensberg mountains range where there was no LEC grid. These areas are very remote and mostly used for grazing. It is not anticipated that anywhere in the near future such a grid will be built in these places. This wind energy potential can be harnessed through means of mini-grids build in the villages around this region and can also be used to supply energy to the nearest towns both in Lesotho and RSA through bilateral agreements. Such an agreement has been entered into before by the national utility when supplying electricity to Qacha’s Nek and when piloting the mini-grids at Sixondo and Dili-Dili in the district of Quthing.

Table 13 shows selected sites, average yearly wind speed (m/s) at 200m height, coordinates and area (m^2) at 3.5km buffer. The areas that show high average yearly wind speeds (11.10m/s) are in high altitudes. These areas include Maloti range, Let’seng in Mokhotlong, and Thaba

Tseka district. At low altitude levels, the average yearly wind speeds are lower as can be seen in selected sites 1, 3 and 4 which are in the foothills of the country and low lying areas of the mountains respectively. The area calculated, only means the possible space where a particular wind speed can be accessible.

Table 13: Selected sites, Yearly Average wind speed (m/s) at 200m height and Area (m^2) at 3.5km buffer

Selected site identification	Average Yearly Wind Speed (m/s)	Coordinates	Area (m²)
1	9.96	27.62595,-29.64252	529437234.43
2	11.10	28.00334,-29.56653	252635071.90
3	9.96	27.98883,-29.32490	200164314.97
4	9.96	28.34658,-29.41882	492740778.91
5	11.10	28.50027,-28.93385	237754512.52
6	11.10	28.58309,-29.63740	851333143.32
7	11.10	28.92547,-29.96527	395900580.19
8	11.10	28.78288,-28.76052	484975238.88

indicates Attributes of Selected suitable areas at 200m height and 3.5km buffer. Places like Matelile, Malealea and other villages appearing in selected area 1 of the wind profile analysis also have a high degree of PV power potential and are easy to access. Similarly, selected area 7 in Qacha's Nek has both high wind and solar energy potential. Almost all mountain ranges top seem to demonstrate a potential for these resources as well. The challenge is that, these places are hard to reach and have little to no road accessibility. In order to tap into these resources in the selected areas, the government of Lesotho will have to invest significantly in road and high voltage power lines. These costs will however be recoverable within a short time span given the fact that a market for power already exists locally and regionally. The increased number of economically disruptive electricity load shedding events in the neighbouring South Africa presents a ripe market for power trading.

Table 14: Attributes of selected suitable areas at 200m height and 3.5km buffer

Selected Area	Selected Area Attributes
1	This places boarders Maseru and Mafeteng. The villages found in this area are Matelile, Malea-lea, Qaba, Ramasoeu and Thabaneng. There are gravel roads linking villages and a tarred road passing through the area. Small hills are present and many cultivated fields.
2	It is in Maseru district along the Thaba-Putsoa range. The villages are interspersed and reachable through gravel roads. There are rivers also such as Setokoane and Leqiliqili rivers. A significant part is mountainous and not easily accessible.
3	This area borders Maseru and Berea districts. It consists of several villages,

	gravel roads and scattered fields. River Jordan passes through the area. It is easy to access.
4	The selected area is in Thaba-Tseka district in a plateau called ’Mats’ooana. It is mostly a mountainous terrain with patches of fallow and cultivated fields. A number of small villages could be observed within the demarcated area but a larger portion is without houses. A gravel road is used to access the place.
5	This area is in the Maloti Mountains range. It overarches the borders of Botha-Bothe and Leribe districts. It is a high altitude area mainly used as rangeland with cattle posts in various places. No village was spotted anywhere. It is generally hard to reach and some parts only accessible through a gravel road.
6	The area spans some parts of Mohale’shoek and Qacha’s Nek. Some scattered fields and villages could be observed. It is mostly mountainous and hard to reach. It can be accessed through a gravel road.
7	The selected place is in Qacha’s Nek. The villages observed in this area are Mosafeleng and Ha Ramatseliso which has a border to a nearby South African town called Matatiele. The place can easily be accessed through a good gravel road currently being upgraded to tarred road. Cultivated fields close the villages could be seen.
8	This area is in the Mokhotlong district. The following rivers were found: Khubelu river, Tlholohatsi river. A gravel road to Mononts’a is present in this place. A school is observed to be built in this area. A portion of wetlands exists towards the south. Other areas are hard to reach.

4.2.5.2 Selected areas and wind farms

The places that have low to no housing occupation have been prioritized for the generation of greater amount of wind energy. For example, suitable area 2, mainly found in Thabaputsoa range, would be best suited for generation of higher amount of wind energy. The cost of wind farms and their generation capacity is shown in . The total estimate of building each wind farm and evacuation of energy is shown in the last column of the table. Area 3 and Area 6 wind farms were calculated based on the future projected costs of wind farms as portrayed in Table 3. These are the only wind farms that are anticipated to be built within the period intended in this IRP.

Table 15: Cost of wind farms and their generation capacity in the selected area

Suitable Area	Type of Plant	Turbine cost (Million USD/MW)	Turbine rated capacity(MW)	Number of Turbines	Plant Capacity (MW)	HV line length-Substation (km)	Cost of HV line (M/km)	HV line Total Cost (Million USD)	Total Plant cost (Million USD)	Estimate System Cost (Million USD)
1	Wind Farm	1.75	2.8	10	28	4	386,760	0.09	49	49
2	Wind Farm	1.75	2.8	20	56	5	386,760	0.12	98	98
3	Wind Farm	0.825	2.8	15	42	6	386,760	0.14	34.65	35
4	Wind Farm	1.75	2.8	30	84	7	386,760	0.16	147	147
5	Wind Farm	1.75	2.8	25	70	3.5	386,760	0.08	122.5	123
6	Wind Farm	1.075	2.8	10	28	15	386,760	0.35	30.1	30
7	Wind Farm	1.75	2.8	40	112	10	386,760	0.23	196	196
8	Wind Farm	1.75	2.8	30	84	7	386,760	0.16	147	147

4.2.5.3 Wind Analysis at 15km Buffer

In analyzing the wind resource availability and selecting suitable places for generating power through wind potential at 15km buffer, a similar procedure was followed as in analyzing it at 3.5km buffer. At this buffer level, most of the country with acceptable wind speeds for wind power generation is covered within the buffer zone.

There are few places outside this buffer where the resource is high recording around 11.10m/s average yearly wind speed. These places have been identified in Figure 25 and digitized. As in global irradiation on panel, the Drakensberg Mountains along Qacha’sNek and Mokhotlong boarder with South Africa (SA) indicate high levels of the wind speed resource. These places are however very difficult to access and exploit the abundant renewable energy resources available in them. However, there are nearby SA towns with existing grid network. With the currently and growing power deficit in SA, government support of renewable energy generation, agreements can be reached between Lesotho and SA for power export from these regions.

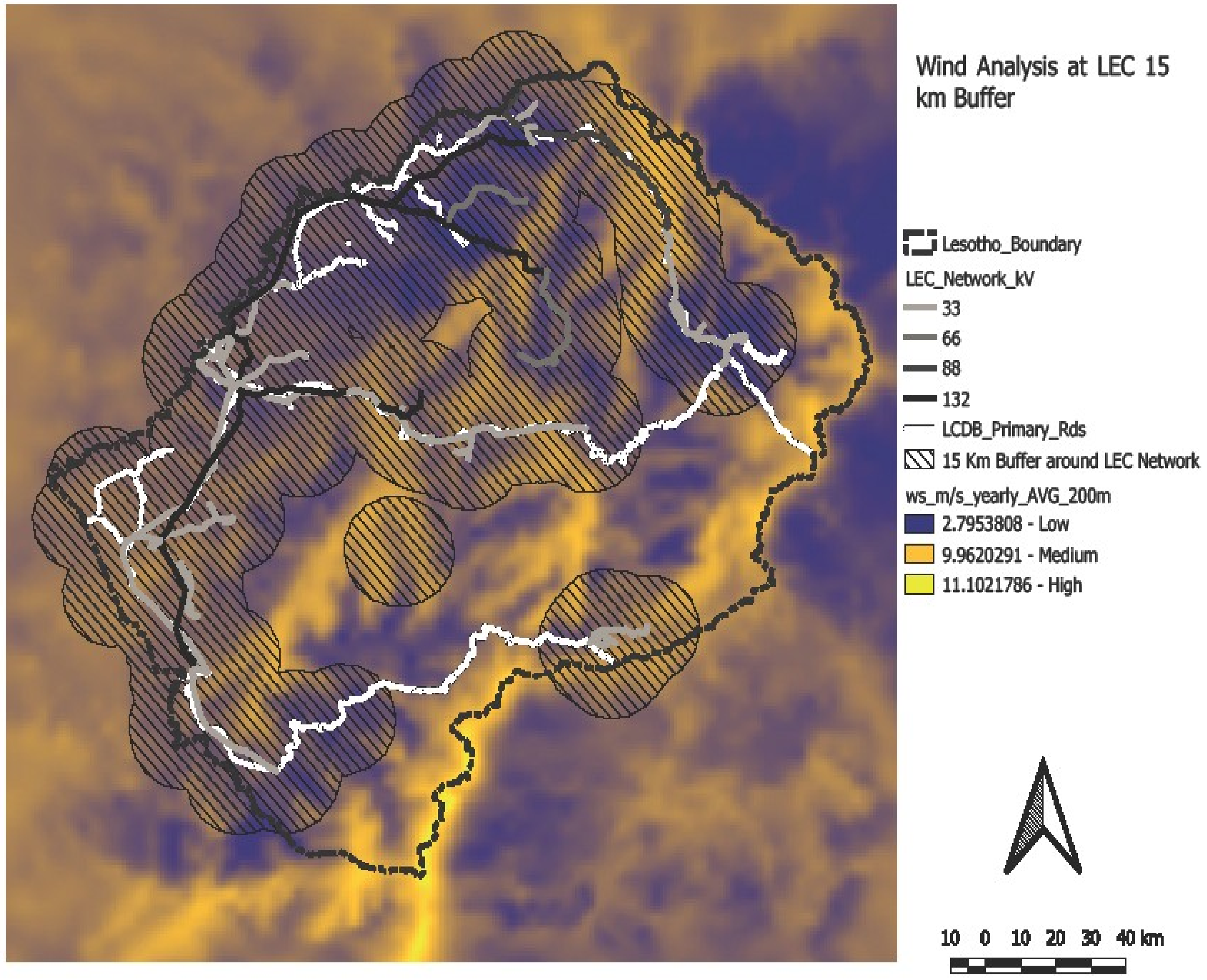

Figure 24: Wind Speed Analysis and 15km Buffer around LEC Grid

Figure 25 illustrates wind analysis at LEC 15km buffer with suitable sites for wind energy generation digitized. There are five suitable sites identified outside the 15km buffer zone with medium (9.96m/s) to high (11.10m/s) average wind speeds. Site 3 has access to the primary road network around Sani site and then runs along the Drakensburg Mountains in Mokhotlong and Qacha'sNek districts. Currently, there is a development of a primary road network construction from Qacha'sNek to Sehlaba-Thebe national park making most of the site 3 area easily accessible. When the envisaged development of the LEC line from Mazenod to Qacha'sNek takes place, the wind speed resources around Thaba Putsoa range, Semonkong and Seforong would be easily accessible since there would be corresponding road infrastructure development during construction.

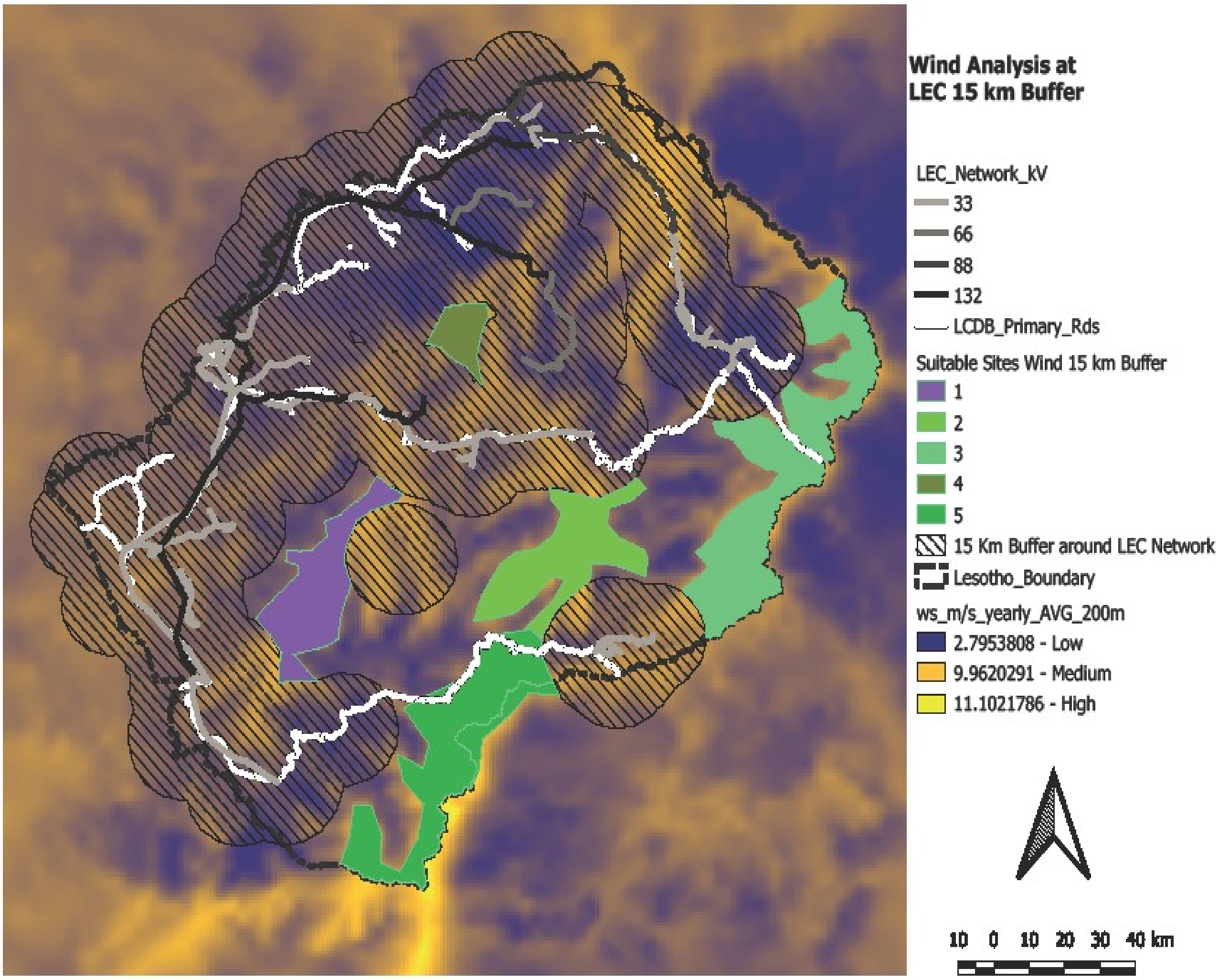

Figure 25: Wind Analysis and Suitable Sites at LEC 15km Buffer

Table 16 shows selected sites, Yearly Average wind speed (m/s) at 200m height and Area (m^2) at 15km buffer. The five identified sites depicted in Figure 25 can be located using the central coordinates. The estimated areas of the sites have been derived using spatial analysis by determining the area of the vector digitized. The selected sites (2 and 3) that have high wind speeds are part of the Central and Drakensberg ranges respectively.

Table 16: Selected sites, Yearly Average wind speed (m/s) at 200m height and Area (m2) at 15km buffer

Selected side identification	Average Yearly Wind Speed (m/s)	Coordinates	Area (m^2)
1	9.96	27.80431,-29.91212	736907613.25
2	11.10	28.54101,-29.79598	828098914.30
3	11.10	29.22553,-29.56145	1555694090.51
4	9.96	28.22246,-29.24570	210222253.60
5	9.96	28.16621,-30.30656	1197961617.09

4.3. Hydro Power Analysis

The software for analysis of hydropower potential TauDEM (Terrain analysis using digital Terrain Modelling software) could not be available due to resource constraints and time available for the study. However, it is appreciated that due to the intermittent nature of wind power and solar, the introduction of Hydropower would bring a greater stability to the power supply in the country since it is dispatchable.

4.4 Proposed IRP and Scheduling

The proposed places of power supply over the study period are aligned to the type of energy source that Senatla et.al had proposed should be brought online in the years specified. The places proposed for generation seemed feasible and economically sensible to be prioritized.

presents the proposed IRP that responds to cost effectiveness for Lesotho for 2022 to 2040. It is cost effective because places that are in close proximity have been grouped together to reduce logistics costs. Solar generation has been mostly prioritized because it is cheaper than wind generation. The projected demand was derived from the logarithmic extrapolation of Lesotho electricity demand from 2022 to 2040.

The suggested power plants have been drawn from the foregoing analysis of wind resources and solar energy available in Lesotho. It is suggested in the plan that 28MW wind power and 30MW solar power from Area 1, be added the same time because generation will be done from the same area, that is around Matelile in Mafeteng district. This will reduce power wheeling costs significantly since production will be done from the same area. It is proposed again that another 28MW of wind power from Area 6 and solar power from suitable Areas 3, 2 and 4 worth 15MW, 20MW, 20MW respectively be added in 2025. If investment in power generation could be done following this proposed IRP, the country will be set to attain power security and independence within 2035 to 2040. The margin for some imports of electricity was left for the purpose of stabilizing the system due to the intermittent nature of wind and solar energy. Another alternative measure of addressing the intermittency problem, would be to build a mini-hydropower station connected to the grid since it is more stable or pump storage as Senatla et.al suggested for stabilizing solar and wind energy.

Table 17 : Proposed integrated renewable energy plan for Lesotho from 2022 to 2040

Year	2023	2025	2030	2035	2040
Current Generation (MW)	72	130	213	268	342
Projected Peak Demand (MW)	201	218	262	306	350
Energy deficit(MW)	129	88	49	38	8
Covered by Imports (MW)	71	25	20	20	20
Added wind energy generation (MW)	Area 1= 28 MW	Area 6= 28 MW			Area 3 = 42 MW
Added solar energy generation (MW)	Area 1= 30 MW	Area 3 = 15 MW Area 2 = 20 MW Area 4 = 20 MW	Area 5= 25 MW Area 7= 30 MW	Area 6 = 40 MW	
Energy Forecasted Cost (USD/MW)	Solar =1000,000 Wind =1750,000	Solar = 834,000 Wind =1075,000	Solar =587,000	Solar =481,000	Wind =825,000
Total cost of adding local generation (Million USD)	**79.1**	**75.87**	**32.48**	**19.59**	**35**

4.5 Summary

The logarithmic extrapolation of the aggregated demand from different studies predicted demand to reach about 350MW in 2040 which falls below electrification master plan prediction of about 420MW and Senatla et.al study using ARIMA based forecast which estimated 363MW peak on base scenario for 2035. The renewables available in the country and evaluated in the resource base maps, were spatially analysed using geographic information platform (QGIS) in which buffer zones around LEC grid and the secondary road network were determined in relation to the availability of the resource. The results observed from the photovoltaic input map showed that the country has photovoltaic power potential ranging from 2164 kWh/kWp to 2249kWh/kWp even around LEC power lines. Most of the high photovoltaic power can be derived from highlands; that is, along the central range which includes places like ‘Mats’ooana plateau and Thaba-Tseka. Thaba-Putsoa range (Ha Mohale to Semonkong) and Maloti range, especially in places like Mphosong and ‘Moteng, also showed a high level of PV power. Most of these places are remote and difficult to access but those within the 3.5km buffer of LEC grid can be exploited.

Suitable places wherein wind energy can be generated have been identified through digitization of wind resource maps. The digitized areas were labelled mainly for cartographic identification in the presented output maps. These can be observed in all the output maps in the study. In the analysis of wind energy potential at 3.5km buffer zone, the wind speeds were found to exceed 9.96m/s yearly average at 200m height in these areas. This corresponded to about 650 W/m^2 of annual wind potential density that can be derived. Much of the wind resource potential was observed in high places, such as the Central range, Thaba Putsoa range, Maloti range and along the Drakensberg mountains range where there was no LEC grid. These areas are very remote, hard to reach and mostly used for grazing.

The analysis of these renewable energy resources culminated in the design of proposed IRP that responds to cost effectiveness for Lesotho for 2022 to 2040 as shown in Table 17.

Chapter 5: Conclusion and Recommendations

In this chapter, the conclusions drawn from the foregoing arguments emanating from chapter 1 to chapter 4 are presented. The recommendations that natural flow from the study are brought forth for further consideration by subsequent researchers.

5.1 Conclusion

In Chapter One, a brief background of electricity situation in the country and experience in Integrated Renewable Energy Planning (IRP) has been highlighted. Several plans for reliable, safe, and affordable electricity supply were discussed. It further describes the scope of this thesis and formulates the problems that were discussed in the manuscript and therefore, the objectives of this study and justification are formulated. Lastly, this chapter presents the summary of the subsequent chapters of the study.

In Chapter two of this thesis, the state-of-the-art IRP literature review is given. Firstly, the current global and local state of energy is theoretically studied and highlighted. This was done with the objective to provide a broad range and diversity of ideas suggested by different scholars and researchers on how to design, implement and reap maximum fruits of a well-planned out and executed IRP. The benefits and challenges associated with adopting IRP as a planning tool in power sector planning and particularly for Lesotho, were also explored. The methodologies that can be adopted in undertaking IRP by utilities and the energy sector, were discussed and compared, especially those that are relevant to Lesotho.

The methodology of undertaking the study is clearly outlined in chapter three. Desktop analysis was done using Quantum Geographic Information System (QGIS). Renewables resources shapefiles received from Department of Energy were input data files. These were analysed in relation to the existing grid and secondary road infrastructure at 3.5km and 15km proximity values. The electricity demand forecast for the period of the study was done through logarithmic extrapolation. Other procedures done included: GIS map production, renewables mapping, renewables potential analysis from maps (Photovoltaic and Global Irradiation on Panel analysis, Hydropower analysis), proximity analysis, power generation (viable sites for possible PV or wind power generation at specified buffer zones) and optimum (least-cost) IRP procedure. A generic costing model whereby the global current cost of producing a unit of energy at utility scale was used in costing the renewable energy plants.

The presentation of the results was done in chapter 4. The results from studies that forecast the future energy demand of Lesotho were compared to establish the best forecasted scenario that suits the socio-economic conditions of the country. Proximity analysis results of the resource base to the grid, primary road infrastructure and substations at 3.5km and 15km buffer zones were presented. Suitable places for energy generation and grid integration were identified and the amount of energy that can be generated from these places was estimated and evaluated.

The study found that the electricity demand for Lesotho projected through Logarithmic extrapolation is estimated reach about 350MW in 2040 which considerably falls below electrification master plan prediction of about 420MW and Senatla's study using ARIMA based forecast estimated at 363MW peak on base scenario for 2035. Furthermore, it has been found that high photovoltaic power can be derived from highlands areas; that is, along the Central range which includes places such as Mats'ooana plateau and Thaba-Tseka, Thaba-Putsoa range (Ha Mohale to Semonkong) and Maloti range especially in places like Mphosong and Moteng, which also showed a high level of PV power potential. Most of these places are remote and difficult to access yet present a great opportunity for the country to produce sufficient electricity and be power independent.

There are places that demonstrated a high abundance of both wind and solar energy resources. These places form another priority area for construction of wind and solar farms thus take advantage of place proximities, economies of scale and reduce considerable power wheeling and logistics costs. In Mafeteng for instance, the places such as Matelile, Malea-lea and other surrounding areas, have good potential of wind and solar energy resources, hence, suitable Area 1 has been first prioritized to generate both wind (28MW) and solar (30MW) power in the plan. These places are easy to reach since they have good access roads. They are also not in the high mountain areas.

It is observed in the study that the country generally has high to medium global irradiation on panel (GIP) with 2188.27 and 2268.91 kWh/m^2 respectively. Most global irradiation can be derived from high altitude places in the mountain areas of Lesotho. Also, these places are generally less electrified by the national utility due to sparsely distributed population of the rural areas. On the other hand, a lot of free land in the mountains which is generally used for grazing provides an ample opportunity for investment in renewable energy.

Furthermore, there are few places where the GIP is low (1754.85kWh/m^2) and these places are mostly located on the eastern part of the Thaba-putsoa range and central range. There are 11 places which were prioritized since they have medium (2188.27) to high (2268.91) global irradiation on panel yearly average. The places were found in different districts such Mokhotlong (Lets'eng area), Leribe (Maluti range), Berea (Maluti range), Mafeteng (Ts'akholo) and in southern part of Mohale's hoek (Awynskop). The level of irradiation in these places presents a good possibility of returns to investment since more electricity from solar energy can be produced annually.

There were eight areas that showed high potential for wind energy at 3.5km LEC buffer zone. The wind speeds were found to exceed 9.96m/s yearly average at 200m height in these areas. This corresponded to about 650 W/m^2 of annual wind potential density that could be derived as indicated in Figure 9. The sites were not very far removed from 3.5km zone hence making the resource within reasonable reach for any investment.

Much of the wind resource potential was observed in high places, such as the Central range, Thaba Putsoa range, Maloti range and along the Drakensberg mountains range where there was no LEC grid. These areas are very remote and mostly used for grazing. It is not anticipated that anywhere in the near future such a grid will be built in these places.

5.2 Recommendations

The hydro resources were not looked into with greater detail in this study. Further research into them will present a comprehensive IRP for Lesotho. Again, evaluation of wind resources at 50m, 100m and 150m could also reveal another dimension in the resource potential available and design of the cost effective IRP for the country.

The cost effective IRP for Lesotho has been proposed in which was the main purpose for the study. A total of 310MW added into the main grid cumulatively from both wind and solar resources from 2022 to 2040 would result in electricity supply independence for the country. Moreover, this study's purpose was to further inform Lesotho energy policy and renewable energy policy formulation and updating. Other policy instruments that seek to enhance access to renewable energy will be better informed as well.

The policy instruments can further zoom into districts, ecological zones and settlement types and encourage design of IRPs that would suit each of these dwelling zones and address exploitation of existing renewables at any of the levels. This will then require an in-depth study of each of these areas in order to establish the extent of renewables that are present.

Further research can also be done in assessment of hydropower potential using the tools proposed in the study. The results from such a study can contribute significantly to the proposed IRP, perhaps even alter the timelines suggested for the introduction of the renewables presented in the study.

References

[1] M. Bonn and L. L. Götz Reichert, “Energy Security,” EU, EU Communication, No. 2014-38, 2014.

[2] DOE, “2015_Lesotho_Energy_Policy.” Energy Policy, DOE_Lesotho, 2015.

[3] G. Strbac, “Demand side management: Benefits and challenges,” *Energy Policy*, vol. 36, no. 12, pp. 4419–4426, Dec. 2008, doi: 10.1016/j.enpol.2008.09.030.

[4] A. D’Sa, “Integrated resource planning (IRP) and power sector reform in developing countries,” *Energy Policy*, vol. 33, no. 10, pp. 1271–1285, Jul. 2005, doi: 10.1016/j.enpol.2003.12.003.

[5] Z. Hu *et al.*, “Integrated resource strategic planning in China,” *Energy Policy*, vol. 38, no. 8, Art. no. 8, Aug. 2010, doi: 10.1016/j.enpol.2010.04.019.

[6] Joel N.Swisher et.al., “Tools and Methods for Integrated Resource Planning.” UNEP, 1997.

[7] S. et.al Dixit, A. Chitnis, B. Jairaj, S. Martin, D. Wood, and A. Kundu, “10 QUESTIONS TO ASK ABOUT INTEGRATED RESOURCES PLANNING,” p. 28, 2014.

[8] P. Yilmaz, M. Hakan Hocaoglu, and A. E. S. Konukman, “A pre-feasibility case study on integrated resource planning including renewables,” *Energy Policy*, vol. 36, no. 3, pp. 1223–1232, Mar. 2008, doi: 10.1016/j.enpol.2007.12.007.

[9] P. Warren, “A review of demand-side management policy in the UK,” *Renew. Sustain. Energy Rev.*, vol. 29, pp. 941–951, Jan. 2014, doi: 10.1016/j.rser.2013.09.009.

[10] Randall. Spalding-Fecher *et al.*, “Electricity supply and demand scenarios for the Southern African power pool,” *Energy Policy*, vol. 101, pp. 403–414, Feb. 2017, doi: 10.1016/j.enpol.2016.10.033.

[11] E. Hirst and C. Goldman, “Key issues in integrated resource planning for electric utilities,” *IEEE Trans. Power Syst.*, vol. 5, no. 4, pp. 1105–1111, Nov. 1990, doi: 10.1109/59.99359.

[12] L. Gelazanskas and K. A. A. Gamage, “Demand side management in smart grid: A review and proposals for future direction,” *Sustain. Cities Soc.*, vol. 11, pp. 22–30, Feb. 2014, doi: 10.1016/j.scs.2013.11.001.

[13] N. Lenssen, “Local integrated resource planning: a new tool for a competitive era,” *Electr. J.*, vol. 9, no. 6, pp. 26–36, Jul. 1996, doi: 10.1016/S1040-6190(96)80261-2.

[14] A. Mohamed and M. T. Khan, “A review of electrical energy management techniques: supply and consumer side (industries),” *J. Energy South. Afr.*, vol. 20, no. 3, pp. 14–21, Aug. 2009, doi: 10.17159/2413-3051/2009/v20i3a3304.

[15] S. White, “DEMAND MANAGEMENT AND INTEGRATED RESOURCE PLANNING IN AUSTRALIA,” *Effic. Use Manag. Water Urban Supply*, p. 7, 2001.

[16] David Hoppock, and Dalia Patino Echeverri, Sarah Adair, “Assessing the Risk of Utility Investments in a Least-Cost-Planning Framework.pdf,” 2013. Accessed: Aug. 07, 2022. [Online]. Available: https://www.ourenergypolicy.org/wp-content/uploads/2014/01/ni_wp_13-07_.pdf

[17] 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.

[18] F. Umbach, “Global energy security and the implications for the EU,” *Energy Policy*, vol. 38, no. 3, pp. 1229–1240, 2010.

[19] M. Bruck, P. Sandborn, and N. Goudarzi, “A Levelized Cost of Energy (LCOE) model for wind farms that include Power Purchase Agreements (PPAs),” *Renew. Energy*, vol. 122, pp. 131–139, Jul. 2018, doi: 10.1016/j.renene.2017.12.100.

[20] Y. Ghiassi-Farrokhfal, W. Ketter, and J. Collins, “Making green power purchase agreements more predictable and reliable for companies,” *Decis. Support Syst.*, vol. 144, p. 113514, May 2021, doi: 10.1016/j.dss.2021.113514.

[21] 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.

[22] International Energy Agency, “IEA-Renewables-2018 to 2023-Analysis-forecast.” (OECD/IEA), 2018.

[23] REN21 Secretariat, “Renewables 2020 Global Status Report.” REN21, 2020.

[24] IRENA, “IRENA_Future_of_Solar_PV_2019.pdf,” 2019. Accessed: Aug. 04, 2022. [Online]. Available: https://irena.org/-/media/Files/IRENA/Agency/Publication/2019/Nov/IRENA_Future_of_Solar_PV_2019.pdf

[25] W. H. Reuter, J. Szolgayová, S. Fuss, and M. Obersteiner, “Renewable energy investment: Policy and market impacts,” *Appl. Energy*, vol. 97, pp. 249–254, Sep. 2012, doi: 10.1016/j.apenergy.2012.01.021.

[26] IRENA, “Renewable Power Generation Costs 2020,” p. 180, 2020.

[27] IRENA, “IRENA_Future_of_wind_2019.pdf,” 2019. Accessed: Aug. 04, 2022. [Online]. Available: https://irena.org/-/media/Files/IRENA/Agency/%20Publication/2019/Oct/IRENA_Future_of_wind_2019.pdf

[28] B. M. Taele, L. Mokhutšoane, and I. Hapazari, “An overview of small hydropower development in Lesotho: Challenges and prospects,” *Renew. Energy*, vol. 44, pp. 448–452, Aug. 2012, doi: 10.1016/j.renene.2012.01.086.

[29] 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.

[30] P. A. DeCotis and E. D. Cartwright, “Smart Siting and Energy Infrastructure Development: A Challenge to Decarbonization,” *Clim. Energy*, vol. 37, no. 11, pp. 14–18, 2021, doi: 10.1002/gas.22232.

[31] J. Li and S. Li, “Energy investment, economic growth and carbon emissions in China—Empirical analysis based on spatial Durbin model,” *Energy Policy*, vol. 140, p. 111425, May 2020, doi: 10.1016/j.enpol.2020.111425.

[32] B. Lin and R. Tan, “Sustainable development of China’s energy intensive industries: From the aspect of carbon dioxide emissions reduction,” *Renew. Sustain. Energy Rev.*, vol. 77, pp. 386–394, Sep. 2017, doi: 10.1016/j.rser.2017.04.042.

[33] S. Dhakal, “Urban energy use and carbon emissions from cities in China and policy implications,” *Energy Policy*, vol. 37, no. 11, pp. 4208–4219, Nov. 2009, doi: 10.1016/j.enpol.2009.05.020.

[34] K. Amirnekooei, M. M. Ardehali, and A. Sadri, “Integrated resource planning for Iran: Development of reference energy system, forecast, and long-term energy-environment plan,” *Energy*, vol. 46, no. 1, pp. 374–385, Oct. 2012, doi: 10.1016/j.energy.2012.08.013.

[35] J. H. Eto, “An overview of analysis tools for integrated resource planning,” *Energy*, vol. 15, no. 11, pp. 969–977, Nov. 1990, doi: 10.1016/0360-5442(90)90022-T.

[36] J. A. Beecher, “Avoided Cost: An Essential Concept for Integrated Resource Planning,” p. 8.

[37] D. Logan, C. Neil, and A. Taylor, “Modeling renewable energy resources in integrated resource planning,” NREL/TP--462-6436, 10161136, Jun. 1994. doi: 10.2172/10161136.

[38] C. Kuster, Y. Rezgui, and M. Mourshed, “Electrical load forecasting models: A critical systematic review,” *Sustain. Cities Soc.*, vol. 35, pp. 257–270, Nov. 2017, doi: 10.1016/j.scs.2017.08.009.

[39] J. P. Carvallo, P. H. Larsen, A. H. Sanstad, and C. A. Goldman, “Long term load forecasting accuracy in electric utility integrated resource planning,” *Energy Policy*, vol. 119, pp. 410–422, Aug. 2018, doi: 10.1016/j.enpol.2018.04.060.

[40] T. Mai, E. Drury, K. Eurek, N. Bodington, A. Lopez, and A. Perry, “Resource Planning Model: An Integrated Resource Planning and Dispatch Tool for Regional Electric Systems,” NREL/TP-6A20-56723, 1067943, Jan. 2013. doi: 10.2172/1067943.

[41] C. L. McClenahan, “Ratemaking,” in *Wiley StatsRef: Statistics Reference Online*, John Wiley & Sons, Ltd, 2014. doi: 10.1002/9781118445112.stat04728.

[42] J. P. H. S. H.Larsen, “Exploring the relationship between planning and procurement in western U.S. electric utilities - ScienceDirect,” *Energy*, vol. 183, 2019, doi: https://doi.org/10.1016/j.energy.2019.06.122.

[43] Joel N.Swisher et.al., “IRP- IMPROVING EE & PROTECTING THE ENVIRONMENT (UNEP).pdf.” 1997.

[44] M. Mpholo *et al.*, “Rural Household Electrification in Lesotho,” in *Africa-EU Renewable Energy Research and Innovation Symposium 2018 (RERIS 2018)*, Cham, 2018, pp. 97–103. doi: 10.1007/978-3-319-93438-9_8.

[45] T. Hadjicostas, “Demand Forecast_FINAL REPORT (1).pdf.” 2016.

[46] N. G. Society, “GIS (Geographic Information System),” *National Geographic Society*, Jun. 21, 2017. http://www.nationalgeographic.org/encyclopedia/geographic-information-system-gis/ (accessed Feb. 06, 2022).

[47] A. Gastli and Y. Charabi, “Solar electricity prospects in Oman using GIS-based solar radiation maps,” *Renew. Sustain. Energy Rev.*, vol. 14, no. 2, pp. 790–797, Feb. 2010, doi: 10.1016/j.rser.2009.08.018.

[48] T. Hong, C. Koo, J. Park, and H. S. Park, “A GIS (geographic information system)-based optimization model for estimating the electricity generation of the rooftop PV (photovoltaic) system,” *Energy*, vol. 65, pp. 190–199, Feb. 2014, doi: 10.1016/j.energy.2013.11.082.

[49] “Analysis of the performance of photovoltaic systems in Slovenia,” *Sol. Energy*, vol. 180, pp. 550–558, Mar. 2019, doi: 10.1016/j.solener.2019.01.062.

[50] A. S. Joshi, I. Dincer, and B. V. Reddy, “Performance analysis of photovoltaic systems: A review,” *Renew. Sustain. Energy Rev.*, vol. 13, no. 8, pp. 1884–1897, Oct. 2009, doi: 10.1016/j.rser.2009.01.009.

[51] H. Moghadam, F. F. Tabrizi, and A. Z. Sharak, “Optimization of solar flat collector inclination,” *Desalination*, vol. 265, no. 1, pp. 107–111, Jan. 2011, doi: 10.1016/j.desal.2010.07.039.

[52] A. K. Yadav and S. S. Chandel, “Tilt angle optimization to maximize incident solar radiation: A review,” *Renew. Sustain. Energy Rev.*, vol. 23, pp. 503–513, Jul. 2013, doi: 10.1016/j.rser.2013.02.027.

[53] GISGeography, “Geographic Information Systems,” *GIS Geography*, 2014. https://gisgeography.com/what-gis-geographic-information-systems/ (accessed Jun. 10, 2022).

[54] Government of Lesotho, “National-Strategic-Development-Plan-II,” 2018.

[55] T. Hadjicostas and D. Padayachy, “lesotho-electrification-master-plan-grid.” Accessed: Jun. 08, 2022. [Online]. Available: https://nul-erc.s3.amazonaws.com/public/documents/reports/lesotho-electrification-master-plan-grid-1532184999.pdf

[56] S. Gautam and L. Hens, “COVID-19: impact by and on the environment, health and economy,” *Environ. Dev. Sustain.*, vol. 22, no. 6, pp. 4953–4954, Aug. 2020, doi: 10.1007/s10668-020-00818-7.

[57] S. Mahendra Dev and R. Sengupta, “Covid 19 impact on Indian Economy,” 2020. http://www.igidr.ac.in/pdf/publication/WP-2020-013.pdf (accessed Jul. 08, 2022).

[58] BOS, “Energy Statistics Report 2020,” Bureau of Statistics, Statistical Report, 2020.

[59] Z. Dobrotkova, K. Surana, and P. Audinet, “The price of solar energy: Comparing competitive auctions for utility-scale solar PV in developing countries,” *Energy Policy*, vol. 118, pp. 133–148, Jul. 2018, doi: 10.1016/j.enpol.2018.03.036.