Cape Peninsula University of Technology

**GIS DECISION SUPPORT SYSTEMS IN RURAL RENEWABLE ENERGY DEPLOYMENT**

**by**

**CLEMENT MATASANE MATASANE**

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**Supervisor: Prof MTE Kahn**

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## DECLARATION

I, Clement Matasane Matasane, declare that the contents of this thesis, entitled "A Decision Support System in Rural Renewable Energy Deployment in the Vhembe District, Limpopo, South Africa," represent my unaided work. The thesis has not previously been submitted for academic examination towards any qualification. All staff members, research assistants, and data acquired during the study were acknowledged, and all contributors were declared. Furthermore, it represents my own opinions, not those of the Cape Peninsula University of Technology (CPUT).

**Signed**  **Date:** 31 November 2023

## ABSTRACT

Many countries worldwide integrate renewable energy systems (RES) in their future energy plans to reduce the negative impacts of fossil fuel consumption and carbon emissions on the environment and have focused on sustainable energy options. The current need and challenges to use alternative energy sources are driven by the continued rise in fossil fuel prices, increasing population and migration, and energy demand, mainly in developing countries, such as South Africa. In addition, the continuous increase in energy demand, global warming, and other environmental problems related to the negative impact of using fossil fuels have raised severe global challenges. The solar, wind, hydro, and biomass resources and their potential to provide alternative energy sources have not been sufficiently utilised. As a result, RES is increasingly being considered as a potential solution for sustainable energy production and reduction of negative environmental impact. To obtain the suitable potentials, it is essential to assess, estimate, and model renewable energy resources in different locations to provide energy end-users, communities, the private sector, and decision makers with accurate, evaluated, and validated data to promote the construction of solar, wind, hydro, and biomass/bioenergy power plants. Furthermore, identifying suitable locations, the available capacity of renewable energy facilities, influencing factors of renewable energy development, and consumption play an essential role in planning renewable energy plants.

The use of remote sensing (RS) technology and GIS tools enable detailed assessment, modelling, and quantification of RES distribution, abundance, and quality that yield an effective and efficient use of available potential. Therefore, determining the optimal locations, capacity and identifying the spatial influencing factors are essential in developing a scientific planning strategy with validated data. This research aims to create a GIS framework for evaluating alternative locations for wind, solar, biomass, biofuels, and hybrid power plants for suitable rural energy deployment. As renewable energy planning is essential, the model will be a valuable tool for decision support in spatial selection and explicit location planning strategies.

In this study, the available energy potential measurements were developed using GIS and RS mappings as tools to assess renewable energy potentials in the Vhembe District Municipality from the perspective of spatial planning. The study's specific aims are to quantify and map the wind,

solar, hydro, and bioenergy potential from a theoretical level, as well as environmental restrictions, and to analyse the suitability of the location for small power plants.

For other regions, the proposed decision support methodology provides a multi-purpose approach for a complex exploration of RES potentials and their exploitation under specific environments and conditions. As a result, the methodology employed in this study can be used in other study areas to assess renewable energy potential in identifying new profitable regions based on the land suitability results that integrate spatial information from remote sensing. Lastly, from the results produced, the available potential can be used in the mapping process in other regions.

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# DEDICATION

*I devote this work to my late parents Cheli Emmanuel Matasane "thuto ke bophelo….ho ruteha ke molamu le thebe ea bophelo lefatseng ka bophara" and the late, Mamofolo "Mamosa" Benedictine Matasane for their unconditional love and parenting which helped me achieve my goal.*

## PREFACE

The present thesis examines the conditions for developing renewable energy sources (RES) potentials, estimation, and modelling to produce wind, solar, hydro, and biomass energy in the Vhembe District. The thesis used the *Conceptual Framework for identifying the Rural Energy Deployment Applications* tool using remote sensing (RS) mappings, weather estimation, and modeling methodology. For the assessment, estimates, and modelling of the RES potentials at the district level, the proposed method was based on the geographic information systems (GIS), environment, and weather conditions by evaluating and analysing primary and secondary data as well as related calculations to the feasibility of RES projects. The Vhembe District was chosen as a model area for other regions for the unexplored RES potentials but lacked sufficient data for the assessment of RES potentials. The proposed multi-criteria methodology is the combined assessment of the maximum available factors relevant for the feasible exploration of RES potentials at small-scale projects.

The main objectives of this assessment of the RES potentials in the Vhembe District, Limpopo Province, are presented in the following published articles as contributing to the thesis:

1. Examine and present the energy status through the solar radiation estimations using the territorial climatological measurements and the conditions in a GIS map as the essential conditions for such projects. The data is taken from the extra-terrestrial radiation and metrology data of sunshine and cloud as empirical data. Thematic maps were generated from the GIS to access the availability and variation of the global solar radiation at specific locations where the data obtained includes details of temperature, relative humidity, rainfall, and hourly sunshine.

2. Assess and present the available yield of wind energy potentials considering environmental and land use in exploitable areas of wind resources. The data assisted in quantifying and mapping the wind energy potential to meet social needs and analyse the land suitability for wind power plants.

3. Model energy scenarios and develop specific recommendations for and improved planning of future projects on biomass energy potentials in the study region and to find the optimal locations for biomass power plants

4. Estimate the hydro potentials for small-scale projects in the areas through modelling and GIS maps. The assessment of the small hydropower projects for a run-of-river scheme using GIS and maps shows a wide range of significant factors contributing to estimation of hydropower potential.

5. Provide a summary of the GIS tool in all the renewable energy applications (that is, solar, wind, biomass, and hydro) that are suitable for assessing, estimating, and validating each energy potential for utilisation and deployment as the solution for communities, designers, and installations.

Finally, maps of priority locations for wind, solar, biomass, biofuels, and hydro-energy systems were laid to identify suitable areas. The proposed framework was applied at the Vhembe District Municipality, where validated data and permission was obtained from the South Africa Weather Services (SAWS) (refer to Appendix 3). The research aimed to understand better how renewable energy resources could be distributed and their potential for electricity generation. Based on multi-criteria evaluation techniques, the possible distribution for each energy type was defined. The findings are significant for designing renewable energy policies, planning, and understanding the district's economic geography of renewable energy. In addition, the methodology applied in this study applies to other study areas where a similar objective can be analysed for renewable energy potentials.

As part of energy mix and collaborative initiatives, Appendix 1 explores the sustainability and perspectives of the renewable energy policies and economic development on ecological footprints; and Appendix 2 contributes to the renewable energy development with the partnerships by exploring the estimation effects of structural changes and technology innovations on carbon emissions which could be applied to South Africa.

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# CHAPTER 1: INTRODUCTION

## 1.1 Background

Reliance on non-renewable resources for electricity generation poses a significant environmental threat. Fossil fuel consumption is a major culprit behind climate change and air pollution, harming human health and overall quality of life in communities (Singh, 2023).

The world faces two pressing challenges: sustainable development (SD) and climate change. Both require solutions on a global scale, but success hinges on local action. As the saying goes, "think globally, act locally." However, local authorities, especially in rural areas, are often left out of the planning for global SD strategies. This is a missed opportunity. Sustainable rural development (SRD) is crucial for achieving global SD goals. Rural areas can significantly contribute to combating climate change and fostering the transition to clean energy. One key element is energy decentralization, also known as distributed energy. This involves producing electricity or heat close to where it's used, making it particularly suitable for rural areas. Renewable energy sources (RES) are ideal for such decentralized systems (Miramontes-Viña et al., 2023).

According to Dalu et al. (2021), over 90% of rural households in sub-Saharan Africa, where roughly 70% of the population lives, rely on natural forest products. In villages like Sambandou and Mavunde within the Vhembe Biosphere Reserve, these resources provide essential goods like fuelwood, food, construction materials, and income generation. This highlights the significant contribution of natural forests to rural livelihoods in South Africa.

Electricity unlocks economic growth and social progress in rural areas. Yet, many communities lack reliable and affordable power due to limited infrastructure and resources (Chidembo et al., 2024). Renewable energy sources like solar, wind, hydro, and biomass offer a hopeful answer. These provide a decentralized, sustainable way to power rural communities. Renewables are gaining traction as a clean, cost-effective, and reliable alternative to traditional fuels. In remote areas with limited or unreliable electricity, renewables offer a long-term solution. They also reduce dependence on imported fuels and create jobs in the renewable energy sector, boosting local economies.

Access to reliable, sustainable energy from renewables tackles energy poverty and improves living standards. Schools, hospitals, and other vital services can be powered, while agriculture and small businesses benefit. Solar power, for instance, shines in rural areas due to its modular design. Small systems can be installed on individual homes or businesses, while larger farms can serve entire communities (Gerbo at al., 2022).

Wind, hydro, and biomass are also options. Wind and hydro power work well in areas with strong winds or readily available water resources. Biomass energy, generated from agricultural waste or organic matter, offers a sustainable option, especially where traditional biomass sources like firewood are dwindling. While renewable energy sources offer a clean solution, integrating them into the grid presents challenges. Their intermittent nature and unpredictable generation limits make them a complex addition to traditional power systems (Skosana, 2023). However, these same renewables are often ideal for remote locations lacking access to the main electricity grid access and are a promising path for powering rural areas, improving energy access, and achieving sustainable development. However, challenges like financing, infrastructure, and policy frameworks need to be addressed to unlock their full potential. While various renewable technologies exist, the most suitable option depends on factors like resource availability, cost, efficiency, and environmental impact (Ranganathan et al., 2023).

In sub-Saharan Africa, countries like Kenya, Ghana, including South Africa, are realizing the benefits of renewable energy (RE). RE development not only expands electrification and improves energy efficiency, but also helps mitigate climate change, fostering better socio-economic conditions (Ajibade, 2019). South Africa's energy mix heavily relies on coal-fired power plants, contributing roughly 70% of total installed capacity. Crude oil accounts for another 21%, leaving only 9% for all other sources, including renewables (Akom, Shongwe, and Joseph, 2021).

In South Africa, electricity supply plays a pivotal role in the communities and the economy of the country, and in improving the quality of life for the previously disadvantaged majority

(Spalding-Fechera and Matibe, 2003). The demand and access have grown such that the government has had to seek alternative methods for power generation for its industrial development and community upliftment and sustainable development, especially in the remote areas. Hence the option of using renewable energy resources has increasingly been implemented by the government at large.

One of the significant drivers of socio-economic development of a country is its access to electricity. The importance of access to electricity supply compared to other forms of energy is enormous. For instance, its contribution to health, education, commercial and production, agriculture and environmental sustainability has facilitated human development. Moreover, and particularly in the rural areas, access to electricity has helped reduce rural-urban migration in search of jobs and modern facilities. In addition, potential benefits of electricity supply in rural areas include crop irrigation, agro-processing, and preservation of farm produce (Kemausuor *et al.,* 2012).

The necessity to achieve sustainable economic development, which would be environmentally friendly, safeguard natural resources and would not contribute to social tensions, increasingly drives attitudes in development strategies and plans for a range of economic activities. This is vital for achieving the best solutions in every country, especially in South Africa. Sustainable development is understood as a lasting ideology of social change, as a compromise which reconciles environmental, economic, and social goals and benefits for our society. In the context of sustainable development, energy development is the ability to ensure sufficient access to energy sources for the public (Šliogerienė *et al.,* 2011).

In addition, sustainable energy provision is regarded as a major challenge, especially in Africa where large proportions of the rural population do lack access to basic energy services. This is particularly prominent in sub-Saharan Africa, and it has prompted many donors, multilateral organisations, and states to pay specific attention to improving the situation of lack of access to modern energy services (Jonker-Klunne, 2011).

Renewable energy has become a driving force in the effort to sustain the earth's natural resources and to improve the users' quality of life. Renewable energy systems are environmentally friendly compared to conventional energy systems. Renewable energy sources are the preferred option as they do not produce any physical pollution, especially green-house gases. They do not exhaust any natural resources, and the inputs they use are abundant in nature. The disadvantage of these sources is that the power from renewable sources is intermittent; therefore, it is difficult to provide a stable energy supply using only one renewable energy source. One more drawback of stand-alone renewable energy systems is their dependence on short and long-term weather and climatic conditions. However, combining two or more renewable energy sources into a hybrid system often helps to overcome this limitation and reduces reliance on conventional energy resources.

It is a fact that conventional energy systems have detrimental effects on the environment, and renewable energy systems (RESs) seem a fitting solution to these problems. However, it is impossible not to affect the environment while producing energy (Tsoutsos *et al.,* 2005). In other words, each RES has negative effects on the ecology and the environment, although these effects are considerably more tolerable than those of conventional energy systems. Therefore, renewable energy resources have advantages over conventional energy systems in terms of environmental acceptability. Nevertheless, before adopting RESs, comprehensive analyses should be conducted to identify the best locations which are associated with highest potentials and at the same time are environmentally favourable.

Decision making is an important component of investments, logistics, allocation of resources, etc. Geographers and spatial planners are interested in decision problems which are based on geographically defined alternatives. These alternatives are evaluated with respect to their spatial arrangement. Many geographic information system (GIS) applications provide crucial information for decision making which support site selection procedures in various research areas, such as natural resources management, environmental pollution and hazard control, regional planning, urban development, and utilities management. These complex problems require simultaneous evaluation of many criteria. For this purpose, multi-criteria decision making (MCDM) can assist decision makers to select the best alternative energy option (Jankowski, 1995). Accordingly, many spatial planning or management problems can be solved by GIS-based multi-criteria decision analysis (MCDA) or in other words, spatial MCDA (Malczewski, 1999).

Another methodology is the artificial neural network (ANN) based model used by Fadare *et al.* (2010) to predict the solar energy potential in Africa. Most data were obtained using NASA GEO satellite database for the geographical and meteorological data of 172 locations in Africa for the period of 22 years. The results obtained showed that solar radiation can be predicted for any location without solar radiation data, but with comprehensive meteorological data of the specific location only (Fadare *et al.,* 2010).

## 1.2 The Essential Use of a Spatial Decision Support System

Making decisions about which type of renewable energy option to implement in the specific location is a typical strategic planning problem for municipalities and financial institutions requiring to integrate the energy systems within the communities. The use of the analytical tools of GIS coupled with MCDM to formally create a spatial decision support system (SDSS) is one way of providing this needed approach for bank decision-makers. An SDSS is designed to support decision making in an unstructured or semi-structured situation where the problem is complex and not amenable to human analysis alone (Zhao, 2002). Therefore, there is a need to augment the power of GIS with the additional analytical capabilities suited to a particular problem.

Geographic Information Systems (GIS) are playing a key role in analysing the potential of renewable energy (RE) for electricity and heat production. Researchers are developing sophisticated GIS models to aid in planning for renewable technologies. These models can help replace or supplement existing energy sources, or even bring power to remote areas lacking infrastructure. Policymakers, utility companies, planning commissions, and researchers across environmental, economic, and energy fields can all benefit from these powerful analytical tools. It's important to note that assessing RE potential typically involves a step-by-step reduction from the theoretical potential to account for technical, economic, and market realities (Melnikova, 2018).

Furthermore, renewable energy adoption faces challenges related to energy availability, including power output, resource location, and infrastructure limitations. However, GIS technology can help assess resource availability remotely, supporting decision-making and the development of energy-saving strategies. GIS goes beyond just data; it's a platform that allows users to analyse and model human activities and their impact on the environment. This capability makes GIS a powerful tool for promoting sustainability in several ways: designing renewable energy infrastructure, supporting energy system planning through potential assessments, energy simulations, building energy demand analysis, site selection, and visual impact assessments (Li and Feng, 2023).

Mlisa (2007) reported that spatial problems typically involve a set of geographically defined alternatives from which the decision-makers can choose a preferred option. This includes ideas that support better informed decision-making for the social benefit of a community. In this regard, GIS is described as a system that supports the process of designing and evaluating spatial decision problems based on spatial relationship principles of connectivity, contiguity, proximity, and overlay methods. Given the points above, a multi-criteria approach is required for the evaluation of renewable energy options for optimal utilisation of available energy resources.

It is believed that the integration of GIS and MCDM techniques offers significant potential for facilitating data management and visualisation, enhancing the efficiency and effectiveness of the decision-making process for assessing the renewable energy options, and providing optimal usage of resources for supply. The challenge remains on how to combine all the renewable energy resources into one system that will give the decision makers better options of energy development and implementation in the locations. GIS is the ultimate decision support environment for amassing knowledge about a place. The layering of various site-assessment data gives the strongest potential picture of a location, and the impact that development will have on the surrounding environment (Walsund, 2013).

Snyman (2002) reported that there are numerous decision support systems (DSSs) being developed worldwide, and the concepts have been applied to many facets of life where computer-aided graphical interfaces have been used to display user-friendly images of the assumed or simulated effects of changes to a system.

It is worth examining the legislation of newer municipal policies that could encourage groups of individuals, communities, and local authorities to invest in micro/small generation of any renewable energy system of their choice based on findings, after this study, per location identified or selected.

The successful implementation of these renewable energy sources through their potential assessment at micro/small generation scale would involve a lot of intelligent decision making, planning, and monitoring by the community and local authorities, since the approach at this scale would need effective tools to strategically site and assess the potential of renewable energy sources available geographically using GIS. The methodology will be applicable and acceptable as the renewable energy sources have geographic potential which are suitable for geographic analysis in the strategic planning of new facilities within communities and by local authorities.

## 1.3 Research Statement

Despite GIS being adopted, implemented, and integrated within renewable energy research with high expectations and on small-scale, with their potential for contributing geospatial analysis and visualisation methods for awareness, building decision support systems have been demonstrated in several projects (Resch *et al.,* 2014). However, broad integration of GIS and energy system models for specific locations such as Vhembe District is still missing.

Wakeyam and Ehara (2011) noted that there are different circumstances between rural areas and cities for the use and assessment of renewable energy potentials and energy demand. As a result, to develop renewable energy facilities effectively and efficiently, systematic, and accurate evaluation of the renewable energy potential is important for successful implementation of the systems to optimise their availability for energy supplies.

Based on existing forecast studies, and on each country's renewable resources, decisions about which renewable energy portfolios should be prioritised for national investment for development need to be made (Atef and Gervet, 2012). There are challenges and questions at the heart of the renewable energy economics which our decision makers are seeking to answer using different models and support tools to determine the potentials and availabilities per their regions. For example, various research studies have shown different systems. Voivontas et al. (1998) developed a decision support system by using GIS for the evaluation of renewable energy resource potential and conducted a financial analysis of renewable energy investment in Crete, Greece. The evaluation techniques in this early study were designed specifically for the local area in Greece. Aydin et al. *(*2010) developed a GIS-based environmental assessment of wind energy systems for spatial planning. A wind potential map of Turkey was identified as both potentially and environmentally feasible the wind turbine locations within the study area. In the study, a decision support tool for site selection of wind energy turbines was developed in the GIS environment using a fuzzy decision-making approach (Aydin et al., 2010).

Ramachandra (2007) reported that to tap the potential of renewable energy sources, there was a need to assess the availability of resources spatially and temporally using GIS along with remote sensing (RS). This would help to map the systems of resources and demands on spatial and temporal scales and would be well suited for identifying these potential zones (Iglesias, 2013).

It is still important, however, to understand the environmental impacts associated with producing power from renewable energy sources such as wind, solar, geothermal, biomass and biogas, and hydropower (Verma and Datta, 2013). In addition, Tegou et al. *(*2007) reported that as renewable energy sources tend to be highly site-specific, it is important to know where they are available in addition to their quantitative assessments and potentials. A staggering 75% of the world's unelectrified population lives in Sub-Saharan Africa (SSA), with roughly 500 million residing in rural areas (Babayomi et al., 2023). Achieving both universal energy access and reduced carbon emissions, as outlined by the UN's Sustainable Development Goal 7 and the Framework Convention on Climate Change, requires a multifaceted approach. While local renewable energy is a key solution, widespread knowledge of its physical, social, and financial aspects is crucial for its effectiveness (Beriro et al., 2022).

Musango (2012) developed a framework that incorporates a technology assessment approach, namely, system dynamics, within the broader scope of technology development for sustainability. It integrates three key elements: technology development, sustainable development, and a dynamic systems approach. It provides a guiding process of applying the framework to energy technology assessment theory and practice within the context of sustainable development. The framework is termed the systems approach to technology sustainability assessment (SATSA). Based on the SATSA framework, she developed the bioenergy technology sustainability assessment (BIOTSA) model to test the outcomes of biodiesel production development in the Eastern Cape Province of South Africa (Musango, 2012).

The exact type and intensity of environmental impacts varies depending on the specific technology used at the geographic location, and several other factors. In this study, a GIS-based decision support planning and mechanism is conceptualised to understand the current and potential environmental issues associated with each renewable energy resource available for optimal utilisation in the region for energy needs. It also aims to measure and compare performances of different energy scenarios according to the defined factors of the design. As per the user-defined specification, it does not exclude constraints and factors that address environment, energy, social, political, and economic considerations. The results may help build a developmental vision for sustainable energy systems based on locally available natural resources and facilitate a transition of national energy and environmental policies towards sustainability throughout the province.

Baban and Parry (2001), Chapman and Thornes (2003), Biberacher et al., *(*2008), Beccali et al., (2009), Aydin et al., (2010), (Olugbile, 2011), Coetzee at al., (2013) and many more have stressed the need for governments, donors, and local stakeholders to have a GIS-based infrastructure that would act as a decision support tool for all energy actors involved in policy making, energy planning and management, and the local authorities who are to enforce the decisions agreed upon in the implementation of these systems.

Cormio et al., (2003), Banks, D. and Schäffler, J. (2005), Amigun et al., (2011), Angelis-Dimakis et al., (2011), Lopez et. al., (2012). and naming few, have quantified renewable resource potentials, and comparing their results is difficult because of the different assumptions, methodologies, reporting units, and analysis time frames used There is currently no national resource-based study on renewable energy potentials across technologies that has been published due to challenges of unifying information for all the geographical areas and technologies available.

Using the GIS in planning, implementing, and monitoring of renewable energy within the poor and urban environment is quite a challenging yet rewarding process that is still relatively new in South Africa, and especially in the Limpopo Province. As a result, extensively evaluating the renewable energy resources and their potentials in the Vhembe District Municipality area and availing them to decision makers and interested parties in Limpopo Province and regionally as a spatial system with open access would help in energy planning and locations for infrastructure.

This research assesses Vhembe District Municipality and investigates what kind of renewable energy resources are available and how feasible they are to be used for generating electricity. To do that investigation and energy calculation for site modelling to have a renewable energy system, its components must be designed.

## 1.4 Motivation for the Research

Renewable energy is becoming an increasingly important source of energy for many countries. South Africa, with its slow-growing economy, energy crisis and needs, increasing energy consumption and high reliance on coal in electricity production is also looking for renewable sources of energy to develop to supplement its power generation, especially in remote areas and among disadvantaged communities.

South Africa has been actively developing renewable energy systems over the past years; however, the ratio of the renewable portfolio is still relatively low; moreover, the role of solar, wind, biomass/biogas, hydro-and geothermal power is very insignificant in the country in improving the quality of life and energy needs for urban and rural areas.

Furthermore, though fossil fuels currently dominate global energy consumption, they are finite resources that will eventually deplete. As a result, their environmental and health impacts necessitate a worldwide shift towards renewable, sustainable energy sources (Ayua and Emetere, (2023). Moreover, rapid increase in greenhouse gas emissions in turn will cause noticeable GDP losses and global climate destabilisation, bringing a range of uncertainties for sustainable future development in South Africa and all over the globe. Thus, the ability to create conditions for renewable energy development is crucial for South Africa.

The overall motivation is to increase the awareness of renewable energy potential and utilisation in rural communities. This will alleviate future climate and energy uncertainties by identifying various pathways to increase energy sustainability and independence in the face of global and regional insecurity related to energy opportunities and identification of energy efficiencies and mechanisms. It will also identify areas where local energy resources can be found and utilised optimally and effectively.

This research supports the overall improvement of sustainable energy options to the communities by:

1.4.1 Increasing community resilience to energy system interruptions for their needs.

1.4.2 Increasing economic opportunities both at a macro energy provision scale and improving local economies which support alternative energy systems and maintenance of those systems.

1.4.3 Enabling potential economic development by way of community-based heat and power facilities which could be owned and operated autonomously by the community.

1.4.4 Identification and exploitation of low-cost, low impact and sustainable energy sources.
1.4.5 Provision of a consistent overall strategic policy and planning framework for community planning.
1.4.6 Incorporation of clearly defined energy policies and decision making regarding rural development.

The primary motivation for my research is to develop a GIS-based tool that serves multiple practical purposes as well as integrates all energy resources within the area and expands on the work done by others in the RES sitting field.

The foundation of this project involved compiling, reviewing, and organising the necessary data into a spatial database that supports location suitability and optimal analysis, as well as model development, sensitivity analysis, and the production of a location maps suitable for development.

By making this information more readily available to decision makers and the public, I hope to stimulate and enhance discussions about energy development, and by creating a tool that assesses many of the criteria involved in energy project location, I intend to provide a practical context for those discussions.

One important outcome of this research will be the ability to integrate this tool into decision support systems (DSS) or more specifically, *spatial decision support systems* (SDSS). SDSS are used to address complex, multi-faceted spatial problems, such as land use planning and renewable energy sitting, which require informed judgments rather than calculable solutions. Since the inception of computer-aided GIS, one of its primary uses has been land use planning; in fact, the evolution of GIS has largely been a response to the needs and techniques of land use planners and developers (Malczewski, 2006). The research and framework presented here will draw on well-documented land use planning theory and research using GIS, and although it will rely on SDSS theory to inform some elements of its design, the primary focus will be on the GIS portion of this combination that can serve as a part of an SDSS for all the renewable energy system locations.

## 1.5 Objectives of the Study

The main objective was to assess, estimate and model the renewable energy potentials (solar, wind, hydro and biomass/ bioenergy) that can be exploited to meet the regional energy demand for the community and commercial use. The use of spatial decision support system through application of GIS and remote sensing mapping has been applied for the Vhembe District Municipality in Limpopo Province. The evaluation of the renewable energy systems was performed to determine the potential of the resources in the region for the interest of domestic and commercial enterprises in small or micro scale production.

## 1.6 Description of the Study Area

The study domain and characteristics forms part of the Limpopo Province bordering Botswana, Zimbabwe, and Mozambique through the Kruger National Park. It shares borders with Capricorn and Mopani District Municipalities in the Southern and Eastern directions respectively. The Vhembe District Municipality Area one of the 5 districts of Limpopo Province of South Africa. It is the northernmost district of the country and shares its northern border with the Beitbridge District in Matabeleland South, Zimbabwe. The municipality is in the North of Limpopo Province and its district capital is Thohoyandou. For administrative purposes, the district, as shown in Figure 1.1, has been divided into 4 local municipalities, namely Makhado, Thulamela, Musina, and Mutale, with the population approximately 1,3million, according to South Africa Local Government (Ndwakhulu, 2007; Statistics South Africa, 2011). The district is the second lowest on access to infrastructure amongst districts in the province, with a high unemployment rate of 53% and a poverty rate standing at 32%, one of the lowest socio-economic areas in the Limpopo Province. The land is very fertile and good for agriculture. A large part of the land falls under the tribal authorities. This makes it difficult for development to take place, as the land tenure system is not favourable to commercial development. The population comprises 54,4% women and 45,5% men, with 51,3% of the population being under the age of 20 years. The district settlement pattern is largely rural, with approximately 774 dispersed villages and 287 190 households (Statistics South Africa, 2011).

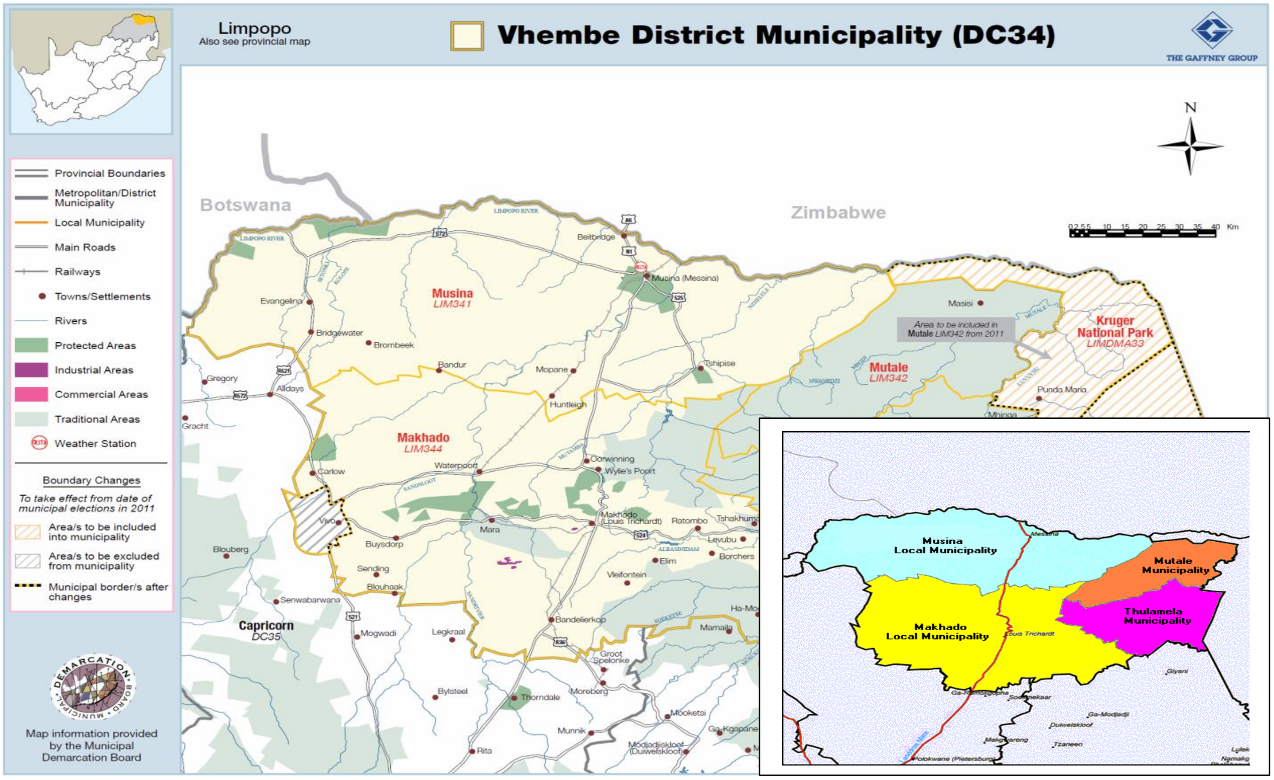


Figure 1.1: Topographic map of the Vhembe Local District Municipality (Source: Ndwakhulu, 2007).

### 1.6.1 Agricultural Strengths and Context

Agriculture is the second largest sector after community services. The agriculture sector currently employs 22% of the labour force and contributes 3% of the GDP. If well supported, the agricultural sector has the capacity to absorb more entrants to the labour market because it is labour intensive. There is potential for the development of mining and tourism, especially ecotourism (Statistics South Africa, 2011).

### 1.6.2 Climate Conditions of Vhembe District Municipality

Vhembe District lies between 22° 58' to 05, 56" southern longitude and 30°27' to 26, 37” eastern longitude and extends over an area of 25,597 km$^2$. Table 1.1 shows the average annual environmental conditions for the region.

Table 1.1: Climate change for Vhembe Region

| **Month** | **Air Temperature (°C)** | **Dew Point (°C)** | **Relative Humidity (%)** | **Daily Solar Radiation - Direct (Mj/m²/d)** | **Wind Speed (m/s)** | **Length of Day (Hrs)** |
|---|---|---|---|---|---|---|
| January | 23.9 | 17.4 | 67.2 | 20.6 | 2.5 | 13.8 |
| February | 23.4 | 17.7 | 70.2 | 19.6 | 2.4 | 13.2 |
| March | 22.7 | 17 | 70.4 | 19.2 | 2.1 | 12.6 |
| April | 20.6 | 14.7 | 69 | 20.8 | 1.8 | 12.6 |
| May | 18.2 | 11.2 | 63.6 | 23.4 | 1.6 | 11.4 |
| June | 15.6 | 8.1 | 60.8 | 22.3 | 1.6 | 11.2 |
| July | 15.6 | 7.7 | 59.4 | 23.3 | 1.7 | 11.3 |
| August | 17.3 | 8.6 | 56.5 | 24 | 2.1 | 11.7 |
| September | 19.5 | 10.4 | 55.6 | 23.6 | 2.6 | 12.4 |
| October | 20.9 | 12.9 | 60.3 | 20.1 | 2.9 | 13 |
| November | 22.1 | 15.1 | 64.5 | 19.4 | 2.8 | 13.6 |
| December | 23.3 | 16.7 | 66.4 | 19.7 | 2.5 | 13.9 |
| **Annual** | **20.3** | 13.2 | **63.7** | **21.3** | **2.22** | **12.5** |

### 1.6.3 Available Renewable Energy Resources

The district has 15 main commodities as Table 1.2 shows, which smallholder farmers produce to improve their livelihoods and create employment in the communities. These include tomatoes, mangos, litchi, citrus, avocados, garlic, bananas, macadamia nuts, vegetable gardens, poultry, fish, guava, livestock (cattle, sheep, goats, and pigs), and backyard vegetable producers (Ndwakhulu, 2007). With such commodities, a waste to bio-energy plant could be built to enable the communities to use their waste material and turn it either into a valuable product that can benefit them in meeting their energy needs, or a marketable product as the source of income in supplying waste to a bio-energy plant that could be developed within their area. This will enable the communities to have a cleaner, healthier environment with potential job creation and access to some improved form of energy that improves their living standards.

The municipality is mainly rural in nature and the citizens are dependent on agriculture as the main economic activity to sustain and improve their livelihood (Ndwakhulu, 2007). The municipality is populated by many farmers who could further be supported using renewable resources such as their livestock waste for economic development and increases employment. In addition, with the availability of land, potential crops such as soya beans and sweet sorghum present the opportunity to be commercialised at scale with a view to biodiesel power production.

According to William et al., (2021), remote communities historically relied on diesel generators for electricity. However, advancements in technology and decreasing costs have made hybrid renewable energy systems a more attractive option for these off-grid locations. As a results, access to clean, affordable, and reliable energy is critical for economic growth and human development. Yet, millions lack this necessity, relying instead on traditional biomass and coal. This hinders progress towards sustainable development goals (Akpahou et al., 2023). Biogas is a promising renewable energy source under investigation. Organic waste materials are broken down in biogas digesters to produce biogas. Studies like those at the Vlakplaats (3,861 kWh/day) and Waterval (21,777 kWh/day) plants show that biogas digesters can generate consistent and significant amounts of electricity (Mabaso et al., 2020).

Table 1.2: Number of smallholder farmers in Vhembe District per main commodity group for waste to energy products (Ndwakhulu, 2007)

| **Commodities** | **No. of smallholder farmers** |
|---|---|
| a) Backyard gardens | 644 |
| b) Bananas | 409 |
| c) Citrus | 16 |
| d) Fish | 81 |
| e) Garlic | 39 |
| f) Guavas | 128 |
| g) Litchis | 4 |
| h) Livestock (cattle, sheep, pigs and goats) | 15 646 |
| i) Macadamia nuts | 512 |
| j) Mangos | 758 |
| k) Piggeries Farms | 6 |
| l) Poultry | 992 |
| m) Tomatoes | 2015 |
| n) Vegetable gardens | 2300 |
| **TOTAL** | **23 636** |

With the Limpopo River cutting across the district to Zimbabwe and Mozambique, there is a very high potential for micro and macro hydropower generation, for example in the Mutale district which cuts across Lake Fundudzi.

Water resources come from the Nandoni Dam, which is supplied by the Lutanandwa, Dzondo, Dzindi, Mvudi, and Luvuvhu Rivers. The Vondo Dam carries water from the Mutshundudi River, and Damani Dam is provided by the Mudaswali River. There is also an underground water supply which is managed by the Department of Water Affairs (DWA). The DWA is trying to protect these resources from any contamination, and controls borehole applications and borehole users to protect the water catchment areas. It is responsible for ground water and rainwater harvesting and desalination, conservation of water catchment areas, and improving the system of water management and water policy reform including pricing and irrigation policies to ensure that these natural resources are preserved and sustainable for future development and community needs.

Table 1.2 shows that there is potentially sufficient wind and solar energy within the district to develop micro and macro wind and solar farms to meet community expectations and energy needs. There is still huge amount of work to be done the energy assessment and its potential, hence the critical need for the use of GIS and RS.

## 1.7 Expected Outcomes

The following outcomes are presented through published articles on the assessment of the RES potentials in the Vhembe District as presented in the following format:

1.7.1 Examine and present the energy status through the solar radiation estimations using the territorial climatological measurements and the conditions in a GIS map as the essential conditions for such projects. The data is taken from the extra-terrestrial radiation and metrology data of sunshine and cloud as empirical data. Thematic maps were generated from the GIS to access the availability and variation of the global solar radiation at specific locations where the data obtained includes details of temperature, relative humidity, rainfall, and hourly sunshine.

1.7.2 Assess and present the available yield of wind energy potentials considering environmental and land use in exploitable areas of wind resources. The data assisted in quantifying and mapping the wind energy potential to meet social needs and analyse the land suitability for wind power plants.

1.7.3 Model energy scenarios and develop specific recommendations for and improved planning of future projects on biomass/bioenergy potentials in the study region and to find the optimal locations for biomass power plants.

1.7.4 Estimate the hydro potentials for small-scale projects in the areas through modelling and GIS maps. The assessment of the small hydropower projects for a run-of-river scheme using GIS and maps shows a wide range of significant factors contributing to estimation of hydropower potential.

1.7.5 Provide a summary of the GIS tool in all the renewable energy applications (that is, solar, wind, biomass, and hydro) that are suitable for assessing, estimating, and validating each energy potential for utilisation and deployment as the solution for communities, designers, and installations.

Finally, the maps of priority locations for wind, solar, biomass, biofuels and hydro-energy systems are overlaid to identify suitable locations. The proposed framework was applied to the Vhembe District Municipality. The research contributes to a better understanding of how renewable energy resources could be distributed and their potential in electricity generation. Based on the techniques, possible distribution for each energy type is defined. The findings are significant for designing renewable energy policies, planning, and understanding the economic geography of renewable energy in the district. In addition, the methodology applied in this study is applicable to other study areas where similar objective can be analysed for renewable energy potentials. The decision-makers and stakeholders can use chapters 3 to determine solar availability; chapters 4, similarly provides the availability of wind; chapter 5 provides the biomass/bioenergy availability; chapter 6 provides the hydro availability; and chapter 7 summarises all the renewable energy availabilities for the area.

## CHAPTER 2. LITERATURE REVIEW

This chapter presents a thorough literature review of the proposed research based on the current research conducted and the available methods. These research methods are related to the renewable energy potentials and assessment of wind, solar, biomass/biogas, and hydro-energy. They are examined separately on their potential and optimal energy generation per location based on other resources and availability for small-scale or higher electricity production in rural and urban areas.

The expected outcomes of the proposed project will utilise the templates for data collection, planning, and review for energy potentials made available by the Vhembe District Municipality. These will give soft formats of the optimal sites for areas of potential solar, wind, biomass/biogas, and hydro-systems provided to the municipality and educators for future use and applications.

This is worth examining to legislate newer municipal policies that would encourage groups of individuals, communities, and local authorities to invest in micro/small generation of any renewable energy system of their choice based on findings after this study per location identified or selected.

### 2.1. Introduction

South Africa's energy crisis has prompted discussions, even with Russia, about evaluating the cost-effectiveness of coal, nuclear, and green energy sources for electricity generation. This analysis could inform better energy management decisions to expand power supply and accessibility for South African communities (An and Mikhaylov, 2020). Further, the South Africa's Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) aims to boost private sector investment in renewables, particularly solar power in the sun-drenched Northern Cape province. Studies using multi-criteria decision analysis techniques suggest the province has the potential to generate a massive 369 TWh to 679 TWh of solar energy annually, exceeding the country's current electricity needs (van der Merwe, Waldo, and Brent, 2020). Another study by KeChrist et al. (2021) highlights South Africa's heavy reliance on fossil fuels like coal. They propose using methane from biogas as a renewable alternative for electricity generation through combined heat and power plants.

Realising that the lack of modern energy is worsening poverty in rural areas, even though there is no specific or quantifiable amount of renewable energy sources to be provided to the rural people indicated in the *National Climate Change Response White Paper* (South Africa, 2004) on renewable energy, the South African government is committed to this policy document which is intended to give a much-needed thrust to renewable energy, particularly in rural areas. The policy also envisages various measures to integrate renewable energy into the mainstream energy economy (Klunne, 2012). This policy has been launched against the background of a massive campaign of electrification in South Africa and a liberalisation of the energy sector, including transforming the electricity distribution sector into regional and rural electricity distributors. Some of the main benefits of the policy will be the provision of renewable energy for rural communities, small schools, and clinics far from the national electricity grid.

The deployment of solar energy to rural areas will increase the availability of lighting and power the equipment used for commercial production and, most importantly, free women and children from collecting firewood. All these measures are geared toward the Sustainable Livelihoods Approach to speed up progress in poverty elimination concerning development priorities. This calls for immediate intervention to develop efficient and safe technologies to relieve women from the burden of hard labour in cooking, collecting water and domestic use. In addition, short and medium-term goals should be developed to meet these challenges regarding the electricity infrastructure by applying innovative grid concepts and renewable technologies.

The adoption of renewable energy technologies and promotion of green energy is being recognised internationally as a way towards independence from fuel oils and being widely exploited as a new environment with rapidly growing applications (Vagiona & Karanikolas, 2012).

There are two main driving forces in the countries behind renewable energy development throughout the world: the current threat of global warming and climate change and the need for countries to secure their energy production (Iglesias, 2013). Ramachandra (2007) reported that renewable energy comes from the natural resources that are constantly replaced in nature on a human timescale, such as sunlight, wind, rain, tides, waves, and geothermal heat, which is why they are commonly accepted as vital energy sources for future life in the world.

All these technologies, their factors, and their applications are accompanied by uncertainties and complexities, which are difficult to control by decision-makers without significant expertise. It is therefore appropriate to develop an effective distributed energy system planning tool that decision-makers can easily use under various spatial measures (Gao & Ren, 2011). As a result, proper assessment of their potential is essential in planning and promoting renewable energy technology (Pillai & Banerjee, 2007).

## 2.2 Energy Demand

Throughout human history, renewable energy sources have been utilised. Ancient Greeks used solar energy by orienting buildings in a way that allowed sun radiation to enter them. Likewise, obtaining energy by burning wood or animal wastes, so-called biomass energy, was the primary energy resource for humanity for centuries. Today, the importance of renewable energy is commonly accepted due to limited fossil fuel resources and significant environmental concerns associated with fossil fuel burning and carbon dioxide ($CO_2$) emissions. Omer (2008a) states that the increase in consumption of fossil fuels induces the release of greenhouse gases. Mainly, developing and industrialised countries must take some precautions to reduce their emission levels while preserving their economic development. In addition, Elliot (2007) points out that one of the best options is to adopt renewable energy and increase energy efficiency to decrease the negative impacts of climate change.

In sub-Saharan Africa, people still lack access to electricity and experience poor supply quality due to cost and reliability. Approximately 580 million people live in rural areas without access to bulk electricity. Overall, the electrification rate in sub-Saharan Africa is around 30% (60% urban; 14% rural) (IEA, UNDP, and UNIDO, 2010).

South Africa is rich in mineral resources, with an extensive mining industry. It is ranked first for platinum production, second for gold production, and fifth in coal production in the world (Ward & Walsh, 2010). The RSA energy economy requires new energy capacity to sustain its energy demand supply and consequently for its investment return to evaluate the options of the different energy mix, especially as there is vast population growth and migration in the country.

Energy demand in RSA is consumed in many sectors: commerce, manufacturing, commercial, transport, residential, power generation, agriculture, residential, and street lighting (Masungo et al., 2011). Transportation is one of the largest consumer sectors for petroleum products, followed by the manufacturing sector and other sectors such as agriculture, tourism, power generation, and government. In addition, energy plays a significant role in human lives, especially for households in low-income and rural areas experiencing inadequate energy services and inconvenient and unhealthy fuels. Hence, it is essential to meet basic needs and achieve social and economic development goals (Winkler, 2006). These include prioritising smallholder agriculture, rural schools, clinics, roads, and communication infrastructure within the country. Analysing and predicting energy potential and demand is crucial for the community, government, and stakeholders, and there is substantial literature to be studied.

According to Zawilska et al. (2012), South Africa’s electricity demand rate is expected to increase by a high percentage in the next 20 years. As more than 90% of the country's power generation is currently generated from coal, the government has developed initiatives and programmes to increase energy supply from renewable energy technology by 16% in 2030. This is supported by the Department of Energy's Strategic Plan for 2010/11 to 2012/13, which stipulates that 16% of the country's electric energy should be generated from renewable sources by 2030.

Thus, developing countries are currently faced with challenges to increase their energy production to accelerate development and raise their community living standards while considering $CO_2$ emissions to increase energy efficiency to reduce pollution, governments must prioritise using and adopting renewable energies. In addition, countries should focus on the end-user-oriented approach to achieve sustainable human settlements' development goals. The actions to be taken by the governments should incorporate renewable energy sources into the national energy matrix.

Current scientific reports confirm that renewable energy resources can alleviate poverty in developing countries by creating employment and business opportunities (Karekezi & Kithyoma, 2002). These energy resources can be used for various domestic and economic requirements such as cooking, heating, lighting, powering schools, clinics, and commercial enterprises and farming. They mainly reduce the time children spend out of school collecting wood, waste, and fuel for traditional use at home and improve their quality of health (Cabraal et al., 2005).

South Africa is a developing country with dual economies which are developed and developing, both of which exist side by side and are reflected in highly unequal access to socioeconomic amenities and services (Klasen, 2000). The previously disadvantaged people are still living in abject and chronic poverty despite the demise of the Apartheid government in 1994 (Klasen, 2000). Modern energy, especially electricity, is still a luxury despite various efforts of the government to make this available and accessible (Balachandra, 2011). In South Africa, energy is one of the critical challenges within its energy policy development, particularly ensuring that rural areas have access to electricity, especially within the country (Amigun *et al.,* 2011). Despite *National Climate Change Response White Paper* (South Africa, 2004), which stated that by 2013, 10 000 GWh of electricity would be from renewable resources, mainly biomass, wind, solar, and small-scale hydro-projects, the government is raising the project targets on renewable, but little has been happening. According to Pegels (2010), on the available renewable energy projects data, shows that little has been channeled to the rural and remote areas of the country for sustainable development in energy mitigation and needs.

## 2.3 Renewable Energy and Sustainable Development

For rural electrification, sustainable development is key to meeting community social development. Energy is critical to virtually every country's economic and social development of South Africans. In the way that it is being produced, transported, and used, it contributes to local environmental degradation, such as air pollution (emission of carbon dioxide), and global climate change challenges, principally global warming. In addition, providing affordable, adequate, and reliable modern energy supplies to most South Africans remains a significant challenge, even though access to electricity has increased since the first democratic election in 1994. With the current electricity production from coal and fuels, these methods of producing and using energy have environmental and health effects that are increasingly endangering welfare. The critical challenge is shifting the adoption to a cleaner energy supply and more efficient use while continuing to extend affordable access to modern energy services, particularly for poor rural and urban communities (Winkler, 2005). Hence using renewable energy means low environmental impacts on local, regional, and global (Munthe, 2009). In addition, using these abundant renewable energy resources rather than only exploiting fossil fuels as electrical power resources makes a more equitable allocation of resources and does not exhaust resources. As such, rural electrification as sustainable development is essential and should be allowed to use the pertinent technology (a distributed generation or autonomous system). The criteria for providing electricity to the rural areas require energy services that will be easily accessible and secure for everyone.

## 2.4 Why Renewable Energy Technologies?

The term ‘technology’ originates from two Greek words, namely 'techno', meaning art, the capability to create something, and 'logos', meaning word or human understanding. Hence, 'technology' is the science and systematic discussion of virtual arts. More generally, technology is a system of means to ends that uses technical artifacts and social information (know-how). Grübler (1998) demonstrates the concept of applied science as a broad spectrum, thus emphasising its inseparability from the economy and societal setting in which it develops. In turn, the societal and economic context is shaped by the technologies built up and used.

Renewable energy supplies are needed for the great efforts to provide the people with better services and resources, not the least of which are access to electricity, but also to increase employment (more industry and commerce) and improved mobility (Banks and Schäffler, 2006). Winkler (2005) reported that the fundamental reason for using renewable energy systems is that they are precise and renewable.

Beginning with this literature review, one would ask the simple question, why renewable energy? This research covers the challenges and available renewable energy potentials in the Vhembe District Municipality, regarding how they can benefit the community by overcoming the energy demand and supply enough energy for domestic use, irrigation, and commercial production. Further, to determine the availability of renewable resources and how optimally they can be used for the energy supply in any category to be mentioned.

The current energy supply in South Africa is primarily coal based and, if used at the current rate, it will last a century. Large power plants will need to be replaced in the next 30 years and alternative energy supply options need to be considered. In addition, coal has many applications and will need to be conserved for future use. However, this represents a severe environmental threat to the country and the world (Banks and Schäffler, 2006).

The thought of using renewable energy rather than fossil fuels is not a novel idea. Fossil fuels such as petroleum and wood are non-renewable resources; hence, their utility is finite. Renewable energy resources are realistic alternatives to the overuse of earth's non-renewable resources. People have benefited from, employed, and even worshipped renewable energy sources in different ways for thousands of years. Hence determining renewable energy potentials is essential for assessment, analysis, and optimal use of community energy demands.

This phase is carried out to explore a variety of interrelated data and information from books, journals, research, and the Internet, serving as background for this study. Numerous technology studies acknowledge the feedback loops affecting technology development, and a common conclusion is shared that technology growth is neither simple nor linear (Masungo, 2009).

Renewable energy development in the region can serve as a mechanism to limit the environmental impacts of energy use, improve the local economy, and increase community participation in local environmental management (Cosmi et al., 2003; Khan et al., 2007). Planning the development of renewable energy sources into existing electrical systems has been conducted via two main approaches: GIS for discovering resource potential and decision-making techniques and mathematical programming for modeling and optimising energy planning. The following chapter provides more information regarding the literature review of previously conducted research in these areas and how it relates to the current research presented.

The lack of adequate energy sources is only one of the developing world's many problems. It is more and more apparent that our current dependence on fossil fuels is threatening our environment, economic system, and health. To reduce climate change risks, the world needs to achieve a rate of $CO_2$ emissions per round of gross world product that is roughly a 60% – 70% reduction below the current level. This stands for an end to the fossil fuel-based energy economy and a gradual transition to an entirely different energy system that ultimately relies on renewable sources of energy (McIntyre, 1997).

Large-scale utilisation of these renewable energy resources will also reduce carbon dioxide emissions, thus contributing to an improved local and worldwide environment (Dincer, 2000). Bradbrook and Gardam (2006) have expressed the same sentiment by accentuating that the priority of the poor is to meet and satisfy basic human needs such as jobs, food, health services, education, housing, clean water, and sanitation. As a result, energy plays an essential role in ensuring the delivery of these services (Bradbrook & Gardam, 2006). Most of the international community has commissioned scientific reports, and opinions have confirmed the importance of sustainable renewable energy for delivering energy services to disadvantaged rural dwellers (Dalal-Clayton & Bass, 2002).

There are currently a great many people living without access to electricity. Sternberg (2008) and Goldemberg (2010) reported that there are 2 billion people still living without electricity in developing countries, including South Africa. Twidel et al. (2005) reported that scientists recommended that policymakers and governments consider alternative renewable energy sources, including solar, wind, hydro-, and geothermal power. In addition, Twidel et al. (2005) explain how to undertake the necessary steps to expand renewable energy supplies and how to use the energy more efficiently and effectively. Goldemberg et al. (1995) and Najam (2005) argue that reliable, affordable, and less polluting energy sources are widely essential and even indispensable components of sustainable development. According to Edinger et al. (2005), renewable energies are the only power sources to serve the energy demand of a growing and developing worldwide population without causing irreversible damage to the world's climate. Edinger et al. (2005) suggest the importance of innovative research and policy initiatives to exploit potential renewable resources sustainably. In addition, Edinger et al. (2005) take the view that the world population is overgrowing, and there is a growing demand for economic development. These growing demands are also being affected by the need to use renewable energy sources as the environment changes. As such, these demands require exploring renewable energy resources. However, only some energy resources are infinite, and they are non-polluting. Thus, renewable sources become attractive alternatives for sustainable electric energy production. The grounds for the importance of investment in renewable resources are based on three significant drawbacks that characterise fossil fuels: they are finite, their combustion releases carbon dioxide and other emissions into the atmosphere, and these emissions have detrimental impacts on ecological sustainability (Twidel et al., 2005).

In most cases, solar, wind, hydro-, biomass, biogas, and geothermal energy are locally available natural sources that may contribute to covering the needs for various energy services (Ringel, 2004). More specifically, where these energy sources are abundant in

Africa, it will be essential for the policymakers to explore these resources for sustainability and their potential.

As a primary challenge, especially in developing countries, exploiting renewable energy sources and their technologies is still immature (Ringel, 2004). Applications of these sources and their initiatives in developing countries like South Africa still need to be extended. The need to explore renewable energy resources and their potential for domestic and commercial use in rural communities still exists. This is also supported by the *National Climate Change Response White Paper* (South Africa, 2004), focusing on developing renewable energy resources, which presents the South African Government's vision of a climate change resilient and lower-carbon economy and society.

Renewable energy resources are particularly suited to off-grid applications and could improve the flexibility of off-grid energy generation and distribution across the country to some essential loads. This will assist in diversifying energy supplies, improving access to clean energy sources, and reducing the use of fossil fuels, pollution, and $CO_2$ emissions (Winkler, 2005).

## 2.5 Sustainable Energy

Lack of access to affordable electricity is a significant determinant of poverty in sub-Saharan Africa, as ranked last in the global regions in energy consumption per capita. This was reported by Deichmann *et al.* (2010) in their report *The Economics of Renewable Energy Expansion in Rural sub-Saharan Africa*, which assessed options of energy development and barriers to their adoption and sustainability (Deichmann *et al.,* 2010).

Literature shows that sustainable development has been defined in many ways. As such, sustainability implies maintaining components of the natural environment over time (such as biologic diversity, water quality, preventing soil degradation) while simultaneously improving quality of life and human welfare; hence the critical element is a change of life (Skidmore et al., 1997). In addition, the UNDP World Energy Assessment found that, if these renewable energy sources are applied in a modern way, they are highly responsive to general energy policy guidelines and environmental, social, and economic goals (UNDP et al., 2000, 221 and Winkler, 2005).

These must be provided daily for people to enjoy the benefits of sustainable energy development and services (Winkler, 2006). According to Cherni and Hill (2009), energy provision is indispensable to household survival.

Energy generation involves the production and use of energy either from non-renewable or renewable sources or from a hybrid system. Major non-renewable energy systems include coal and oil production (Mega, 2005). Renewable energy systems include hydropower, wind, solar, and tidal. Recently, evolution in research has embarked on interests in environmental and socially harmonious energy resources (Fery et al., 2002).

While consumption of fossil fuels is increasing regardless of their adverse impacts on the environment, today, the world's agenda focuses on sustainable energy systems in terms of both reliability for economic development and benefits for the environment. According to Tester et al. (2005), the definition of sustainable energy is the combination of providing energy equally to all people and protecting the environment for the next generations. The Renewable Energy System has formal approval as a form of sustainable energy that has received much attention recently (Omer, 2008b). Considering these facts, renewable energy sources and their potential, which respond to the needs of current energy challenges and future populations, should be adapted.

Technology terms such as ‘renewable’, ‘sustainable’, and ‘green energy’ can be used interchangeably. The general perception of these terms is that renewable energy sources have environmental benefits. Although the impact of renewable energy sources is less than those of conventional energy systems, some may have significant local impacts and changes in quality of life (Elliott, 2007).

In this research, general issues such as the sustainability of energy, renewable energy systems, global renewable energy status, and trends will summarise the renewable energy status in South Africa, and environmental management of renewable energy systems within the country will be considered. The focus of this research is renewable energy potentials in South Africa about how spatial decision support systems can be used towards optimising availability of renewable energy sources and the different methods of applications. This will highlight methodologies used for the different challenges in renewable energy systems.

## 2.6 Renewable Energy Systems and their Potentials

Worldwide, many existing projects and technologies have economic and environmental benefits associated with renewable energy sources. They are currently assisting in the diversification of energy demand and markets. In addition, they are advantageous in reducing local $CO_2$ and global atmospheric emissions. They are currently providing supply-specific needs for energy services, particularly in developing countries and rural areas. Furthermore, with the current challenges, they can provide new employment opportunities and enhance local production and domestic use (Asif & Muneer, 2007).

Significant challenges surrounding the assessment, analysis, and optimisation of renewable energy systems in South Africa include the financial, social, technical, sustainability, environmental and regulatory aspects of these systems for access by the rural community. A discussion on these issues will be included in the methodology section and the proposed model using the decision support system framework for renewable energy potentials.

For example, the *Harare Declaration on Solar Energy and Sustainable Development* considered cheap, clean, renewable energy essential in improving the quality of life and creating income-generating activities. In the Harare Declaration in 1996, world leaders expressed the need to support renewable energy projects in developing countries and the need for the provision of adequate energy services to improve the living conditions, alleviate poverty, improve health and education, promote small-scale enterprises, and create other income-generating activities, especially in rural and isolated areas, thereby reducing rural to urban migration (U.N. Chronicle, 1996).

The proponents of decentralised renewable energy recognise that most people in the Third World still depend upon wood, animal and vegetable wastes, and animal power to earn their daily livelihood (Ganapathy, 1981).

Awareness of the world's energy problems is greater now than at any other historical period. It is now widely accepted that the energy consumption growth experienced for many years cannot continue indefinitely, as there is a limit to our fossil fuel reserves. Renewable energy is by far the most plentiful alternative energy source for the future to meet the requirements of communities. Finding alternative sources of energy that are both economically and environmentally friendly is crucial for increasing local productivity and improving the quality of life in rural communities (FAO, 2000). Winkler (2005) reported that the most recent estimates of renewable energy potentials had been compiled for the South African Renewable Energy Resource Database by the Council for Scientific and Industrial Research. However, these are available in the form of GIS. maps, and detailed data is unavailable for further development or selection.

Biomass is modeled for wood (unprocessed and processed); hydropower is mapped for macro and micro power generation using cumulative mean flow volume along river lengths; solar radiation is modeled through annual and monthly solar energy and reviewed per horizontal square meters. Finally, wind is modeled to estimate the mean annual wind speed at 10m height above ground level. As a result, the system needs deeper information and a specific model and analysis for the location.

## 2.7 Global Renewable Energy Status

It is commonly accepted that energy is a necessity for quality of life by providing basic needs such as heat, light, and power for entertainment devices and labour-saving appliances (Akpinar et al., 2008). Energy consumption worldwide is expected to rise by around 2% by 2030. It is essential that during this expected rise in energy use, the economy and environment are also considered very important in developing these systems.

Renewable energy is becoming more popular worldwide because it minimises the effect of fossil fuels, which cause greenhouse gas emissions (Ozgur, 2008). In addition, since fossil fuel sources are limited, human beings will be forced to find ways of utilising renewable energy systems in the future (Akpinar et al., 2008). For example, Larsson (2003) and Lee and Yoshida (2012) reported that the European Union White Paper on Energy in 1997 set goals to increase the share percentage of renewable energies in gross domestic energy consumption in 2010 from 6% to 12% and recommended the use of renewable energy such as waterpower, wind power, and biomass as energy sources. These would play an integral role in the future (Janke, 2010).

Zavadskas et al. (2005) noted that developing countries have different environmental and socioeconomic systems than most developed countries. However, they noted that the best sustainable urban development should be compatible with political, economic, social, cultural, and other situations of any examined country, which can be adapted into natural economic, social, political, cultural, institutional, technological, environmental, legal/regulatory, education situation systems, legislation/regulation and provision situations of an existing state to influence total efficiency performance (Zavadska et al., 2005).

One of the essential elements of economic development is continuous and reliable energy production. The development of energy policies that satisfy demand while protecting the environment is of significant concern. As a result, the contribution of renewable energy systems in energy planning and management is essential.

Also, in 2010, UNDP reported that the need for access to modern energy services using renewable energy resources had increased the use of rural electrification with better affordability, improved knowledge, and modern energy services (UNDP, 2010).

## 2.8 The Status of Renewable Energy in South Africa

In 2002, the South African government recognised and published a White Paper on the Renewable Energy Policy of the Republic of South Africa, November 2003. One would say it came after the 2002 World Summit on Sustainable Development, where renewables were positively featured in a summit agenda led by the United Nations (U.N.) for implementing ab action plan to prioritise alternative forms of energy services (Karekezi & Kithyoma, 2003). The Department of Mineral Resources and Energy's *Renewable Energy White Paper*, *2023* established a target for renewable energy contribution above and beyond the current renewable energy contribution. Sebitosi and Pillay (2008) noted that South Africa is gifted with adequate renewable energy resources that could complement the country's energy mix to address the energy shortage and the heavy carbon footprint in the country.

Additionally, the Department of Mineral Resources and Energy's *Renewable Energy White Paper*, *2023* mandated that the nation develop a practical implementation strategy for renewable energy. As such, in South Africa, there are several renewable resources (solar thermal (for heating), solar thermal electricity generation and solar photovoltaic generation, wind generation, biomass, hydropower, wave (ocean) power, and other resources, such as geothermal) with potential to contribute significantly to the energy supply (Banks and Schäffler, 2006). Mabiza (2013) also studied the energy potential and sustainability management of platinum catalyst fuel cell technology in South Africa. The research was to understand the environmental impacts of local production activities and the use of platinum group metals for hydrogen fuel cell technology, fuel in South Africa, and to contribute to the clarification of the environmental sustainability of the national technology hydrogen fuel cell initiative (Mabiza, 2013). Pegals (2010) identified the economic barriers to renewable energy potential by associating costs and risk structures as the main factors in South Africa for investing and planning renewable energy supplies.

Furthermore, during the Energy at the Renewable Energy Summit held in Centurion, Gauteng, south Africa in March 2009, it was resolved that the mid-term review specified in the REWP (2003) be undertaken by the end of the 2009/2010 financial year. A World Bank-funded contract for the review was awarded in February 2010, and the South

African Department of Energy (DoE) announced that the Renewable Energy Policy Review would be released by the end of the first quarter of 2011.

Moreover, there are legislation, regulations, and planning process changes required for acceleration in publishing the Renewable Energy Feed-In Tariff (REFIT) regulatory guidelines. However, there are still challenges until renewable energy is widely adopted. Less than 10% of the intended increased capacity for renewable energy has been reached thus far.

South Africa has excellent solar and appropriate wind resources by international standards. Regarding hydropower development, a micro hydropower station is being constructed, namely the Bethlehem Micro-Hydropower Station at the Sol Plaatje Dam in Free State Province (see Figure 2.8 below), which gets water from the Lesotho Highlands Water Project. With wave power supplies, South Africa is currently in its early development, though it has an extensive coastline with high wave energy potentials.

In recent years, several renewable energy potential mapping methodologies have been developed (e.g., solar irradiation and wind estimation, geothermal and biomass energy) (Maxwell & Renne, 1994; Ivanov *et al.,* 1996; Schneider *et al.,* 2006). These methods can be used as building blocks in enhancing urban planning approaches. However, the methodologies have been developed for micro scale and cannot be applied unmodified for selecting new housing locations (Vettorato & Zambelli, 2009). Therefore, it is necessary to either adapt existing methodologies or develop new ones (Palmas *et al.,* 2011).

Considerations of energy efficiency should be integrated at the start of the land use planning process to guide future development of the sites with the best potential for using renewable microgeneration. These potentials can be developed sustainably by using multicriteria evaluation methods in a GIS to help optimise new settlements in terms of multi-functionality. There is a history of research using such techniques to support collaborative decision-making by providing a framework where stakeholder groups can explore, understand, and redefine decision problems concerning housing location (Jankowski & Nyerges, 2001; Malczewski, 2006; Palmas *et al.,* 2011).

Renewable energy sources in South Africa have the potential to significantly contribute to the country's energy industry, society, and economy. In June 2013, Deputy President Kgalema Motlanthe addressed the South African Green Energy Youth Summit in Cape Town, where he was a keynote speaker. He noted that South Africa had intended to develop renewable energy resources not only to diversify the energy mix, without preferring one energy carrier over another, but also to take full advantage of our endowment in other natural resources. He noted that with infinite renewable energy resources, South Africa has the potential to become one of the world's fastest-growing economic hubs, address environmental impacts, and develop sustainable energy resources (Mothlanthe, 2013).

A key factor in deciding whether renewable energy sources are cost-competitive is the price of electricity. The average energy price in South Africa grew by 25% in real terms thanks to pricing judgments made by the National Energy Regulator of South Africa (NERSA) from 2008 to 2013; it went from 18 cents per kWh in 2007 to 66 cents in 2013, and Eskom planned to raise the price to 103 cents per kWh by 2015. As part of integrating renewable resources into the existing electricity grid, in October 2008, the South African government announced a R150 billion, 5 000 MW solar park to be built in the Northern Cape as part of the interventions associated with the financial incentives and research and development in the country. Furthermore, the South African government introduced several policies, such as the *Renewable Energy White Paper* (REWP 2003), to initiate switching to renewable energy as part of its energy strategy. However, in 2009, the Renewable Energy Summit resolved the challenges of having a mid-term implementation plan awarded and contracted to the South African Department of Energy (DoE) to review the policy in implementing renewable energy strategies.

As a result, for the future development of the nation, South Africa's energy industry, society, and economy all stand to benefit significantly and vitally from the use of renewable energy sources.

### 2.8.1 Grid-Connected Wind-Powered Electricity Generation

Wind energy is one of the oldest natural resources exploited by means of mechanical systems. Wind power extraction is an ancient endeavour, beginning with wind-powered ships and windmills. In the last century, more sophisticated wind power technology was developed, and wind turbines are being constructed to generate electrical power. The main drivers for utilising wind turbines to generate electricity are the very low $CO_2$ emissions over the entire life cycle of manufacture, installation, operation, and decommissioning, and the potential of wind energy to help mitigate climate change. The stimulus for the enlargement of this field was due to the oil crisis in the 1970s and the concern over fossil fuel scarcity (Harborne et al., 2009; Mentis, 2013).

The high rate of population growth in the rural areas, coupled with the low-income generation and willingness to pay (affordability), as well as the high rate of non-electrified areas, have traditionally pushed rural communities to use locally available energy sources, mainly biomass from agriculture residues and forest wood for their daily cooking and heating needs. These have made countries such as Egypt, Morocco, Tunisia, and South Africa recognise and start utilising wind energy potential, and they already have installed several wind farms for communities (Mentis, 2013).

Around the world, there are several sources of renewable energy as well as numerous systems for utilising them. Each has characteristics and needs for implementation per regional or specific location. Wind farms offer the most considerable and significant energy supply for integration into the grid, which significantly improves the shortage of electricity supply in South Africa. Wind being vast potential as a clean energy source makes it a crucial area of research. Wind turbines can be installed onshore or offshore, making it a widely accessible renewable resource. In addition to its role in sustainable development, wind energy is gaining global momentum to enhance energy security and promote economic growth (Abdurahmanov, 2023). Following a global trend towards clean and affordable energy, Benin has significantly ramped up its green energy initiatives in recent years. This push is driven by the country's vast, untapped potential for renewable energy sources, which can significantly contribute to its national energy production capacity (Akpahou et al., 2023). Abdallah et al. (2020) also highlighted energy security as a major obstacle to development in many countries. They proposed that wind power, a renewable energy source, can significantly contribute to poverty reduction, but stresses the importance of providing adequate information.

South Africa has relatively developed initiatives and projects for wind energy exploitation. The Darling Wind Energy Facility near Cape Town is one the first independent power producers generating energy from wind in the country. The facility has been generating an amount of 5.2MW capacity since May 2008 (Moiloa, 2009).

Figure 2.1: Wind turbines at a Darling wind farm near Yzerfontein, Western Cape, South Africa (Liane Greeff (2012)

According to Ramachandra and Shruthi (2005), wind energy is ultimately a solar resource. Wind speed, air density, latitudes, surface roughness, terrain, atmospheric pressure, average temperature, and land use patterns will significantly influence wind velocity to generate ample wind power. These are mainly created because of temperature differences between the earth's latitudes and deflection due to the sea wind's kinetic energy. The wind's kinetic energy is a renewable energy resource with significant worldwide energy production in the world. Mathematically, the total annual kinetic energy of air movement in the atmosphere is approximated around 3 x $10^{15}$ kWh, or about 0.2% of the solar energy reaching the earth (Wilbur, 1985). The maximum technically usable wind potential is approximately 30 x $10^{12}$ kWh/year, or about 35% of the current world total energy consumption, and approximately 36% of this total power can be captured by windmills and converted to electricity (Ramachandra *et al.,* 1997; Ramachandra & Shruthi, 2005).

This means that projects developing medium-sized wind-generation systems will be affordable and of considerable benefit to the nations in the next decade. Klipheuwel Wind Farm is another wind energy constructed by Eskom, which started generating in August 2002 with a total capacity of 3.2 MW. According to Baban and Parry (2001), wind power is one of the renewable energy forms expected to encounter widespread commercial success because it is economically viable and does not produce any physical pollution.

Another development in wind energy is a study on assessing the wind energy potential of the Amatole district in the Eastern Cape Province of South Africa **(**Masukume et al., 2013). According to the classification of wind energy (Class 1), the area is unsuitable for large-scale wind energy development. It can only be used for the decentralised wind energy systems exploitable at 10m or higher for low-speed wind turbines (Masukume et al., 2013). The average wind speed obtained, that is, the wind power density of the site is 47.878 W/$m^2$, less than 100 W/$m^2$. It was concluded that in selecting the appropriate locations for wind energy construction, certain conditions must be fulfilled to enhance environmental benefits and prevent conflicts related to the wind farm siting (location), land use functions for agriculture and keeping cattle (Sliz-Szkliniarz & Vogt, 2011).

This wind velocity (minimum wind speed for wind exploitation purposes) is calculated using the Weibull Distribution per annual energy yield characterised by the probability density function and the cumulative distribution function for a given period interval (Schallenberg-Rodríguez and del Pino (2011).

As a result, the application of GIS on renewable energy planning on wind farms and visual impact assessment of wind parks, apart from the constraints provided by national legislation, site selection, and assessment procedure, must address the technical, physical, economic, social, and environmental aspects of the project to determine whether it is suitable for wind energy development for a particular area. This would give the most common GIS-based strategies to facilitate decision-making in site selection, land suitability analysis, and resource evaluation for wind farms (Baban & Parry, 2001; Tegou et al., 2010). Consequently, GIS can play a significant role as a decision support tool regarding optimum wind potential for locations. Furthermore, it would enable consideration of factors such as the planning, ecology, and physical development of the wind energy system which would overcome the constraints associated with visual intrusion, noise, regulations, safety, animal habitats, hydrology, construction accessibility, and foundation accessibility (van Haaren & Fthenakis, 2011).

Schallenberg-Rodríguez and del Pino (2011) reported that the methodology of using GIS in energy planning would accurately determine wind energy and allow the quantification of the potential for energy production, and at the same time, locate where production would take place.

### 2.8.2 Biomass Co-Generation

Biomass co-generation offers the next most considerable potential compared to wind. Ramachandra et al. (2007) reported that biomass is a renewable source that could account for nearly 33% of a developing country's energy needs. These include aquatic and terrestrial vegetation, biomass wastes, such as municipal solid wastes, municipal bio-solids, animal wastes, forestry, agricultural residues, and particular industrial wastes (Ramachandra et al.), 2007).

In this method, biomass including agricultural and forestry waste is burned, and the heat that results is used to create energy and heat industrial processes. Some 2.7 GW could be implemented competitively over the next ten years. Another example is a study by Alam et al. (2011), which developed a decision support system for planning the logistics of wood biomass procurement for conversion to bioenergy at the Atikokan Generating Station (AGS) in northwestern Ontario. The model used the non-linear dynamic programming method with a general algebraic modeling system computer software. The model estimated the optimal quantity and type of wood biomass supplied to the AGS based on the station's historical monthly power generation schedule (Alam et al., 2011).

Biomass, as one of the most used renewable energy resources in South Africa, provides the most energy and consumption options for Africa's electricity industry. For example, Figure 2.2 shows the relationship between the Eastern and Southern African countries on the proportion of total national energy supply derived from biomass energy use. This estimation is at about 9%, and some data indicate as high as 14% (Banks and Schäffler, 2006). These refer to biomass energy from organic and agricultural wastes, such as wood, charcoal, agricultural residues, and animal waste, as traditionally used (Karekezi & Kithyoma, 2003).

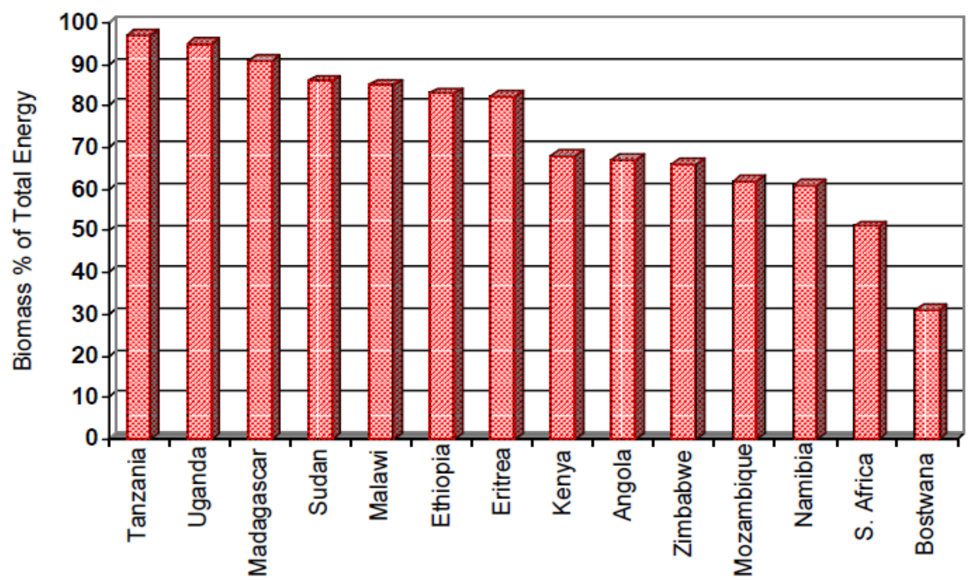


Figure 2.2: Total energy percentage of the biomass energy selected from East and Southern African countries. The figure shows that South Africa has 50% use of biomass resources. (Source: AFREPREN, 2000)

Guta (2012) reported that policy measures should thus target technological innovation both from the demand and supply sides to ensure sustainable production and utilisation of biomass resources that can cater to energy security. Also, they should encompass holistic socio-cultural, economic, and technological renovation to open the market for renewable fuels and assure the sustainability of supply and adoption of appropriate renewable energy technologies (Guta, 2012).

In past years, biomass resources have been primarily used as traditional fuels and are now being promoted as a strategy for sustainable development. As biomass is mainly available locally, it allows the widespread production of energy at reasonable cost and helps to mitigate climate change, develop rural economies, and increase energy security. Thus, numerous methods and tools have been technologically advanced to evaluate the availability of biomass resources regionally or locally. Biomass is the biodegradable (ecological) fraction of products, wastes, and residues from agriculture and forestry and of related industrial and municipal wastes. Besides, biomass can be developed on determination in dedicated energy crops. That is, the residual biomasses derive from the agricultural sector, both in the form of crop residues and animal waste; the forestry sector, from forests' thinning and maintenance; the industrial sector of wood manufacture and food industries; the waste sector; and in the form of residues of parks maintenance and municipal biodegradable (ecological) wastes.

Biomass potentials are classified depending on their theoretical, techno-economical, and sustainable (ecological) availability. Furthermore, the theoretical biomass potential can be assessed based on biophysical and agroecological factors that determine biomass growth and extension, and the residue production fractions. The techno-economical potential is then estimated, considering accessibility, resource competition, biomass logistics, production costs, and all other factors that restrain the theoretical potential.

In addition to the biomass potential assessment, Angelis-Dimakis et al. (2011) added that sustainable potential is a further assessment that aims at evaluating the amount of biomass that can be obtained considering the socioeconomic and ecological impacts of this type of energy project. Constraints may vary according to regional specificities such as forestry, agricultural and industry practices, socioeconomic conditions, and the natural environment.

As part of the energy assessment, one from geographic information systems literature is that of Fernandes and Costa (2010), where biomass residues were found to be economical alternative energy sources. He indicated they are commonly available and often related to site locations similarly represented by GIS data and can be associated with moderate effort for further development. The potential would be using potential biomass residues from forestry/forest products, agriculture, and urban sources, including municipal wastes.

With biomass from wood being assessed from the forest residue biomass, biomass from agriculture from either livestock manure or crop residues, could be evaluated. This method would seek help from the help of the Ministry of Agriculture for information or databases on the number and location of farms and their approximate numbers of livestock.

### 2.8.3 Biofuels

In 2004, Southern African Development Corporation (SADC) member states met in Gaborone, Botswana, to discuss food, agriculture, natural resources, infrastructure, and services. The agreement reached was to consider biofuels as an initiative that presented an opportunity for the region to produce renewable resources. The meeting was the follow-up from the World Summit 2002 on Sustainable Development (WSSD) in South Africa (Takavarasha, 2005). With the implementation of the SADC Regional Indicative Strategic Plan, (2005 – 2020), the region examined its potential for increased ethanol production from the seven energy crops identified, namely oil palm, sweet sorghum, sugar cane, sunflower seed, soybeans, Jatropha, and cassava by country, thus providing a basis for biofuels. Biomass can be supplied by dedicated crops of arboreous and herbaceous species, such as annual crops (corn, soy, sugarcane, sorghum).

Watson and Chavez’s (2011) work used GIS to assess the bioenergy potentials from the feedstocks in eight sub-Saharan African countries in their dryland regions. Using GIS revealed that Africa's drylands have important and potential areas available and agriculturally suitable for bioenergy feedstock production. The methodology used GIS to interrogate a wide range of datasets, aerial photographs, and field verification, and to obtain information from various stakeholders. The work was carried out on the identified dryland regions of Botswana, Burkina Faso, Kenya, Mali, Senegal, South Africa, Tanzania, and Zambia, where well-managed intensification of, or conversion to, bioenergy feedstock production has a low risk of causing detrimental environmental and socioeconomic effects. The study countries were chosen because they already had several different bioenergy initiatives (Watson & Chavez, 2011).

Preston (2009) reported that South Africa has the potential for energy provision in rural areas using cattle manure, regarding which 310 000 rural households have the technical capacity to generate energy from cow dung and human waste for the biogas digesters. He reported that they could independently generate biogas and save the country's energy cost by R325m per year or generate R12 billion in value as a liquified petroleum gas replacement and possibly generate 45 000 person-years in job opportunities. The *Technical Report of South African Cities Network* (SACN, 2009) reported that biogas could also be generated using the municipal waste from sewage, food waste, manure or agriculture waste, and energy crops.

The South African biofuel strategy, adopted during the meeting of the SADC region, Gaborone, Botswana, 2005, aimed to create 55 000 jobs and contribute to economic growth by using home-grown biofuels (SADC 2005). These were needed to re-energise the agricultural sector and proper use of land. However, with these products, several specific areas would need special attention, such as air pollution and greenhouse gas emission reduction, land for energy crops, biofuel programmes, issues of land ownership, water conservation, biofuel programmes and biodiversity and pertinent issues of food security for the country in best practice and goal achievement (Mwakasonda, 2007). Most of the biofuel programmes were envisaged to usher in an array of opportunities, including the following: an all-time opportunity to meet growing needs of energy, significantly raising modern energy access in rural areas; a means to reduce and offset the high cost of importing fossil fuels and an avenue for waste land reclamation (Mwakasonda, 2007). In addition, as part of SADC development in biofuels, research on using sweet sorghum in Botswana was reported by Peloewetse (2007). Peloewetse (2007) reported that the fermentable carbohydrates that can serve as primary substrates in ethanol production demonstrate the renewable energy resource potential of sweet sorghum, as shown in Figure 2.3. Other seeds include Jatropha for energy production in Southern Africa.

Figure 2.3: Agricultural sweet sorghum production for the potential of biofuel production (Source: Khathi, 2007)

Countries such as Botswana, Madagascar, Namibia, South Africa, Tanzania, Zambia, and Zimbabwe have started growing Jatropha in their lands to develop biofuels. Kgathi (2007) argued that it is necessary to use degraded land to grow Jatropha curcas and leave fertile land for food production. This will address concerns about the unsustainability of food-based biofuels due to conflicts in land use and environmental problems. According to Benge (2006), the seed and kernel of the plant contain 35% to 40% and 55% to 60% of oil respectively, which can be used for biodiesel production. Jatropha curcas has the second-highest oil content among all known energy crops. Further, the growth of Jatropha may lead to improved livelihoods due to employment creation associated with the establishment of nurseries and the restoration of degraded lands (Kgathi, 2007). Takavarasha et al. (2005) listed the energy crops recommended by the SADC study on biofuels (SADC, 2005), as shown in Table 2.1.

Table 2.1: Energy crops for biodiesel energy production in SADC (Takavarasha et al., 2005)

| Energy Crop | Ranked | Reasons |
|---|---|---|
| Sugar cane | 1 | Already grown in the region for ethanol production<br>Generates much employment<br>Foreign exchange benefit |
| Soybeans | 2 | Expanded use of biodiesel production<br>Scores high for biodiesel production |
| Oil palm | 3 | Scores high for biodiesel |
| Sunflower | 4 | Ranked fourth because not widely grown in the region |
| Sweet sorghum | 5 | Ranks low because not yet commercially grown |
| Jatropha | 6 | Not yet commercially grown |
| Cassava | | Not a significant crop in the region |

Like other countries and the world, South Africa has identified which species it should grow as part of the energy development in South Africa, and some manufacturers have been commissioned and have started production for the energy implementation process. As several models for biomass and biofuels have been developed to support the decisions over which species to grow, the local climate, morphology, soil characteristics, water, and nutrients needs are commonly used to identify the set of species suitable for a specific area (Aylott et al., 2008).

### 2.8.4 Biogas Digesters

Smith et al. (2011) state that an integrated waste management system uses biogas technology as a clean, renewable, naturally occurring, and underutilised energy source. The gas generated is like natural gas and contains between 50 and 70 percent methane, with the remaining ingredients including carbon dioxide, traces of ammonia and hydrogen sulfide, and carbon dioxide. It can be piped, bottled, stored, compressed, and even liquefied for on-site energy production, storage, and access to heating, cooking, electricity production, and vehicle fuel. The potential benefits to the household include improved food production; energy access; reduced deforestation, erosion, and soil degradation; improved indoor air quality and sanitation; water reuse and recycling; and local job creation. The type of biogas digesters available in sub-Saharan Africa consists of 3 main types: the flexible balloon, floating drum, and fixed dome.

Waste, including food scraps and cow manure, is converted into methane gas by biogas digesters, which are then utilised for cooking and heating. These have yet to be developed and implemented on a large scale in South Africa as in countries such as Asia. According to Figure 2.4, there is a possibility for at least 300 000 households in South Africa, mostly in rural areas, to gain from biogas digesters. Biogas digesters can also process organic waste streams commercially, producing methane for energy. This application has become increasingly common worldwide.

Figure 2.4: Installed biodigester system in the Upper Thukela Area and Richmond area of Kwa-Zulu Natal (Source: SACN, 2009)

The principles of sustainability in waste management strategies are to minimise waste generation and storage to maximise waste recycling and reuse as alternative waste power generation. This has also been encouraged by the National Waste Management Strategy, November 2011, which acknowledges these principles and identifies them as initiatives for a safe environment (DEAT, 1999).

In addition, NERSA has encouraged the private sector to invest independently in power production by tapping into the Renewable Energy Feed-In Tariff (REFIT) Programme. Most industry sectors have been installing wind and solar energy across the country. However, energy from waste could also provide a better opportunity than other renewable energy sources.

### 2.8.5 Concentrated Solar Power

Concentrated solar power (CSP) is a relatively mature technology, but still quite costly. Although full-scale plants have been built, the total global capacity still needs to grow.

Typically, as larger quantities of technology are deployed, costs decrease. This means that the rate of decrease becomes more gradual when large amounts have been deployed.

Given the excellent South African solar radiation resource, the Northern Cape location has excellent solar radiation levels and vast areas of suitable land, could contribute a significant proportion of South African electricity demand, such as Figure 2.5.

Figure 2.5: Photograph of a photovoltaic solar energy facility (tracking technology - from Sunworx Photovoltaic Systems website) (Source: Savannah Environmental (Pty) Ltd., 2013).

Fluri (2009) reported that relevant South African solar data have been gathered and implemented in a GIS programme for implementing large-scale concentrated solar power (CSP) plants. Several maps have been created, and potential sites have been identified, taking account of the solar resource, proximity to transmission lines connected to the electricity grid, land use profile, and its slope for development.

Maphalele et al. (2013) reported that photovoltaic (PV) technology was introduced to South Africa in the 1980s for small-scale off-grid installations, specifically in rural areas. In the late 1990s, larger commercial-scale projects were implemented. However, these projects were still only in the order of tens of kW in size. In 2010, larger commercial-scale projects in hundreds of kW were implemented due to rapidly increasing electricity costs and the need to redress global warming and climate change. In 2013, 18 large utility-scaled projects with capacity of 630 MW and 417MW were constructed as the result of the Department of Energy's REIPPPP, which are about to reach financial closure.

CSP conversion systems are another source of solar power increasingly being implemented in South Africa, though it is more immature than countries like the USA, where CSP technologies have been successfully developed for more than 30 years (Bradsher, 2010; Hang, Jun, Xiao; Junkui, 2008 and Sedler, 2010).

However, as CSP technologies play a significant role in fostering the solar power industry, more suitable methods in spatial planning and project distribution are needed; thus, methodology is another important area to be considered. Poor spatial assessment and planning could bring many unexpected consequences for CSP project planners, operators, investors, and decision-makers. Distribution and return on investment time of CSP projects depends a lot on many spatial and economic conditions, such as solar radiation, land availability, proximity to the grid, local electricity feed-in, retail prices, and financing schemes within the country (Sedler, 2010).

### 2.8.6 Solar Photovoltaic Energy

Solar energy is both environmentally and economically important to every nation. It plays a vital role in the cost-effectiveness of any nation's economy, creating direct labour force employment and fostering micro industry development (Ajayi, 2013). Solar power is clean energy that the government and industrialists should give support to, by reducing the cost of installing solar panels for industrial, commercial, and residential consumers.

Solar photovoltaic (PV) electricity generation involves turning solar radiation directly into electricity in a solar panel. It is a mature technology but much more costly than alternatives for large-scale electricity production. GIS has the potential to analyse solar radiation for power generation. For example, Ayompe and Duffy (2013) used GIS software to assess the energy generation potential of photovoltaic systems in Cameroon using satellite-derived solar radiation datasets.

As with CSP, solar PV is also still on a relatively steep part of the technology learning curve in South Africa. However, costs have decreased significantly over the past years and are expected to continue to decline. Solar PV could become cost competitive for large-scale electricity production and domestic use. Currently, photovoltaic modules are widely used in South Africa for serving approximately 200 000 households for lighting, and access to television and telecommunications, alongside several thousand rural institutions and water pumping purposes. Figure 2.6 demonstrates the wind and CPS power plant installed in the Eastern Cape Province as part of the government initiatives for rural communities off-grid and remote areas. The village is situated 10km from the Hlukela Nature Reserve within the mountainous region of the province.

Figure 2.6: Lucingweni wind/PV energy system and Hlukela Nature Reserve at Eastern Cape (Source: Szewczuk, 2009)

### 2.8.7 Solar Water Heating

Solar water heaters use solar radiation to heat water directly. They should be distinct from PV panels, which produce electricity. Solar water heating is a mature technology: heaters are readily available commercially and have been mass installed in rural and urban areas within South Africa. For a typical household, the overall cost of solar water heating is less than the electricity required to heat the same water at the same service levels. Figure 2.7 illustrates the water heaters installed for households.

Solar water heaters could effectively provide hot water for households using paraffin stoves and coal and wood fires to heat water. This would result in significant social and poverty alleviation benefits through lower fuel costs. In addition, there would be substantial environmental and health, and safety benefits.

Figure 2.7: Solar water heaters installed in Khayelitsha Village, Western Cape (Source: Preston, 2009)

Solar water heaters could provide equal service to the 4.2 million households using electric geysers in South Africa. In addition to the savings to consumers already noted, the country would avoid investing in significant additional power supply.

The use of solar water heaters would further prevent the burning of millions of tons of coal currently powering conventional electric geysers, thus doing away with the associated environmental pollution and mining impacts. The government has recognised this and launched several implementation programmes in 2003/4. These include the 2007 Eskom programme to install one million solar water heaters and the Department of Energy (DoE) programme to roll out another million in 2007.

According to Trollip (2013), a senior research associate with Idasa's Economic Governance Programme, and Marquard (2013), a senior researcher in the Energy, Environment and Climate Change research group at the Energy Research Centre, University of Cape Town, by January 2010 only a tiny fraction of these programmes had been implemented. Around 77 000 solar water-heating units had been installed, replacing less than 2% of existing electric geysers. Further, most of these had been installed in the ordinary course of commercial business that was not under government or Eskom roll-out programmes.

### 2.8.8 Wave Energy

Much of this research has yet to be done in South Africa as it is in its infancy for development and implementation. The theoretical global wave power resource was computed using ArcGis software (Cornett, 2008). Around Africa (Atlantic and Indian ocean coasts), sub-regions were considered during a regional analysis (Mork et al., 2010).

### 2.8.9 Hydro Water Energy

Hydropower generation plays a significant role in global energy production, and several power plants have shown potential for energy supply and feeding the grid for electrical connection. Recent studies have shown that using GIS analysis has helped estimate the hydropower potentials for specific regions (Meijer et al., 2014).

Kölling et al. (2011) and Jonker-Klunne (2011) reported that an analysis of 6 countries, Ethiopia, Kenya, Mozambique, Nigeria, Rwanda, and South Africa indicated the vast potential of mini and micro hydropower in sub-Saharan African countries to cover increasing energy demand and to enable electricity access for remote rural communities. In addition, it noted that 12 % of the greatest hydro potential in Africa is located in sub-Saharan Africa (SSA) due to its geographical conditions and relatively significant energy potential being untapped.

Figure 2.8: The 7 MW hydropower plant in Bethlehem (Sol Plaatje Dam), Free State Province, South Africa (Source: Sanelisiwe Mngomezulu, 2017)

SACN (2009), reported an acute shortage of rural electricity supply in almost all sub-Saharan African countries, and grid-based rural electricity supply is associated with many challenges. Small hydropower technology is one of the best-suited technologies for off-grid power supply, but it is site-specific, affecting the system's design and development. An example is shown in Figure 2.8 for a small 7MW hydropower system developed in Free State Province. These need full, technical, and economical site feasibility, and valuable information is required for the potential developer to estimate the potential data per region and installation.

Dubhani et al., (2006) reported that hydropower generation is a renewable and sustainable energy source to meet global challenges, and it represents a large-scale alternative to fossil fuel generation, contributing only a minimal amount to greenhouse gas emissions and other atmospheric pollution (Frey & Linke, 2002). However, details on the survey and investigation for a potential site offer many challenges.

While hydropower is a safe, sustainable, and dependable energy source that advances governmental environmental and energy policy goals, it contributes a very small amount to the overall energy mix. Thus, harnessing hydro-energy requires an assessment of the water resource, which depends upon the natural processes occurring locally and the terrain characteristics. Accurate and reliable assessment of water resources leads to successful planning (Kurse et al., 2010).

Even though a preliminary indoor selection of potential sites that relies on existing geographical and hydrological data does not dispense fieldwork, a thorough conduction of the site survey will give decision-makers suitable grounds to reach a final set of alternatives with the most negligible impact on hydropower development over other activities, existing infrastructure facilities and the environment (Larentis et al., 2010).

Yi et al. (2010) noted that the success of hydropower development depends on its economic efficiency determined by the power generation performance characteristics according to the plant types and installed capacity. They added that small hydropower plants are generally categorised into reservoir and run-of-river types according to whether they maintain a stable stream flow in the river.

## 2.9. Environmental Management (Planning) and GIS

Using GIS for sustainable development and environmental management balances meeting humankind's present needs while protecting the environment to fulfill future generational needs (Verma & Datta, 2013). Coetzee et al., (2013) reported that geographic information science (GIS) provides the theoretical foundation and applied technology to support planning and decision-making for sustainable development. Hence, it identified economic growth, environmental balance, social inclusion, and culture as the main dimensions of sustainable development.

The growing human population and its demands on the earth's resources generate a need for sustainable practices. GIS allows users across the globe to share ideas on how to meet their resource needs, plan efficient land use and protect the environment from guaranteeing the survival of future generations. GIS technology is an effective tool for studying the environment, reporting on environmental phenomena, and modeling how the environment responds to natural and artificial factors. Understanding relationships within the environment is essential for creating environmental impact reports, designing sustainable management plans, prioritising project areas and funding, and informing the government and the public about environmental concerns. GIS can be used to analyse ecological footprints, improve watershed resource management; and respond to climate change, pollution, and more **(**Muataz, 2009).

Because renewable energy systems are highly site-specific, it is crucial to know where they are available in addition to their potential assessment. A geographic information system (GIS), a computer system capable of assembling, storing, analysing, and displaying geographically referenced information, is an appropriate tool to address these issues (Ma et al., 2005). GIS is also a supportive tool for renewable energy assessment, which is currently used as a decision support tool in regional renewable energy management (Kumar & Shekhar, 2014). Various environmental, transportation, planning, waste management, water resources, forestry, agriculture, housing, and natural hazard applications have been undertaken using GIS modeling techniques (Janke, 2010).

A GIS is a computerised geographical database used to gather, store, integrate, retrieve, and process data on the location and shape of geographic elements and relationships between them from various places or sources. Its geographical data include those which are spatially referenced (location-based data) and contain four integrated components: (1) location, (2) attribute, (3) spatial relationship, and (4) time (Zeng, 2002). Chapman and Thornes (2003) reviewed the role of GIS in climatology and meteorology by discussing methods used to derive and refine spatial climate data, application of GIS and spatial climate datasets in agriculture, ecology, forestry, health and disease, weather forecasting, hydrology, transport, urban environments, energy, and climate change. They noted that it is a computer system coupled with considerable advances in computer processing ability that can handle sizeable high-resolution datasets.

The application of GIS with renewable energies in distributed electricity generation has been the focus of several research projects (Domingues and Amador, 2007 in press). In this field, studies for wind farm location, photovoltaic electrification, or biomass evaluation stand out (Yapa, 1991; Voivontas et al., 1998; Gadsden et al., 2003; Ma et al., 2005; Masera et al., 2006; Yue & Wang, 2006; Ramirez-Rosado, 2007).

The appropriateness of a GIS for locating renewable energy source (RES) facilities is portrayed in Baban and Parry (2001):

2.9.1 It can manage and analyse volumes of diverse multidisciplinary data.

2.9.2 It has the functionality to perform "what if" scenarios to evaluate the effects of different planning policies or to uncover the optimum RES (e.g., wind farm) site among several potential alternatives.

2.9.3 It can be used to model the proposed projects' adverse impacts and suggest modifications to mitigate or minimise them **(**Muataz, 2009).

2.9.4 It integrates and presents the geographical data as per specific project requirements.

A variety of research has focused on the exploration of renewable energy sources using GIS. However, these assessments have been somewhat limited, focusing on simply a single possible source in many cases, with specific research devoted to solar (Ramachandra, 2007; Carrión et al., 2008), wind (Rahman, 2009; Voivontas et al., 1998), and biomass energy (Ayoub et al., 2007; Panichelli & Gnansounou, 2008). In the few instances in which research has explored the potential for multiple resources (Yue and Wang, 2006, Domínguez et al., 2007; Tegou et al., 2007; Schneider et al., 2007), the development of a map for each source was created independently of the other source, or sources, being explored. The South African Renewable Energy Resources Database developed by the CSIR, ESKOM, and DMRE collated the solar, wind, hydro, and biomass maps. The energy potential of each source was modeled within GIS at the spatial scale of one square kilometer. There has been no consideration of the interaction between the different energy options and an optimal plan for utilising all these resources in one system implementation.

The role of GIS in defining renewable energy source potentials is quite extensive as it is an appropriate instrument to utilise due to nature. The suitability of renewable energy source deployment at specified locations is based on a mixture of features that express the fitness of a specific renewable energy source. Finding a desirable position for wind or solar farm usage is a phase of the site selection problem, in which more sites are selected based on a series of characteristics such as price or space. GIS has been used for site selection for many purposes, such as warehouse location (Vlachopoulou et al., 2001), hazardous waste storage facilities (Jensen & Christensen, 1986), and aquaculture (Ross et al., 1993). In these cases, GIS is the appropriate tool to utilise because it can synthesise important geographic and regulatory parameters in the site selection process. The function of GIS for renewable energy site selection has also been explored previously at local, regional, and national levels (Short et al., 2009; Domínguez et al., 2007; Biberacher et al., 2008; Voivontas et al., 1998).

In environmental management, for instance, GIS applications have been used to monitor the environment using satellite pictures such as the Land Cover Maps of Great Britain (Fuller & Groom, 1993) and monitoring wetland changes in East Africa (Haack, 1996).

Some mapping systems have combined environmental data with relevant information, such as promoting sustainable tourism in the Mediterranean region (Giavelli & Rossi, 1999) or using ecological data to map the distribution of biomass in Southern New Mexico (Phinn et al., 1996). Arsenau and Lowell (1992) built a model for tracking the forests, while Johnston et al. (1996) used GIS to model ecological processes, and McKenney et al. (1999) provided a standardised model for solar radiation by utilising a digital elevation model. To explore the temporal variations in land use and water quality of the Omerli Watershed in Istanbul, Turkey, Coskun and Alparslan (2009) created an environmental model. In addition, RS and GIS techniques were also used to analyse water quality and land use assessments. Brown and Affum (2002) proposed a GIS-based environmental modeling system to identify the environmental impacts of road traffic plans. It was suggested that this model might assist planners in testing both the environmental impacts associated with transportation plans and the efficiency of network plans. Store and

Jokimaki (2003) developed a method to generate an integrated habitat suitability index based on GIS, which produced spatial ecologic information associated with the habitat requirements of different species. Mas et al., (2004) proposed a model to predict the spatial distribution of tropical deforestation. Maps for assessing the risk of deforestation were created using satellite imagery. GIS is thus a crucial tool in environmental management. Although it is not the only computer programme related to this topic, environmental policy and environmental management are greatly aided by decision-making on various applications using the GIS (Goodchild, 2003). The GIS tool is equally helpful in this research to assess and evaluate the renewable energy potentials of alternative locations available for energy generation supplies.

Africa is currently developing and experiencing strong economic growth, showing the positive trends in human development indicators by individual factors and measures put in place by each government. As many challenges exist, accessing modern energy will be critical to sustaining these positive signals. Africa, by and large, possesses abundant renewable resources that could spur continued economic growth, accelerate social development, and help the transition to a sustainable energy system that can provide universal energy access to disadvantaged communities and improve the quality of life (Stecher *et al.,* 2013). In February 2009, the African Union Assembly (AUA) of Heads of State and Governments decided to develop renewable energy resources to provide clean, reliable, affordable, and environmentally friendly energy. This was reaffirmed by the African Union (AU) Conference, which was held in Maputo, Mozambique, in 2010 to promote renewable energy systems. (AU Maputo Declaration, 2020).

With such highlights by the African Heads of State, South Africa has embarked on the implementation of renewable energy technologies; as noted that they need to establish an appropriate plan for the deployment of and investment in renewable energy technologies together with the most suitable locations for such investment (Stecher et al., 2013).

Even in Africa, there have been various research studies on exploring energy potentials with different models and systems. In addition, the various methodologies and assumptions used are timeframe, geographical coverage, the definition of potential, biomass resources, and other important driving factors.

In summary, previous research that has utilised GIS to this end was conducted on multiple software packages with specialised programmes for each source (Belmonte *et al.,* 2008). This creates the thought of comparing one set of outputs to another. To provide a user-friendly system that can be utilised to explore the renewable energy potential for multiple sources, there must be integration between the different outputs, or there should be one system to handle all of the analysis. This would supply the users with the ability to analyse outputs for each resource more efficiently and determine the potential for each source based on the standards set through programming. Goodchild (2003) reported that GIS for environmental management varies according to the purpose and may be used as a valid analytical instrument. At the lowest sophistication level, GIS is a tool to produce visual maps for decision-makers and researchers.

## 2.10 Modelling

The generation and distribution of electricity have been analysed and modelled using various methods. These methods have included multi-criteria decision-making (Hobbs & Meier, 1994; Afgan & Carvalho, 2002; Hamalainen & Karjalainen, 1992; Terrados et al., 2009) and the use of the analytic hierarchy process (Xiaohua & Zhenmin, 2002). However, the family of mathematical programming techniques includes some of the most efficient approaches to energy planning. The use of mathematical programming for energy planning, whether renewable sources have been included or not, has been considerable and has taken on a variety of approaches, such as linear programming seeking to minimise capital investment in new sources (Ashok, 2007), to minimise costs of energy flows (Meier & Mubayi, 1983; Cormio et al., 2003; Ramachandra, 2009), or to maximise the use of renewable energy (Iniyan & Sumathy, 2000). More comprehensive models have been developed using multi-objective linear programming (Borges & Antunes, 2003) and goal programming (Ramanathan & Ganesh, 1995; Deshmukh &

Deshmukh, 2009). The model developed in this research will be a mixed-integer, multi-objective optimisation model based on the 'environment-economic' approach, which has been used extensively (Wang & Singh, 2006). These models have varied in implementation, but the general concept is that renewable energy planning has two competing objectives. One objective seeks to minimise the environmental impact or maximise renewable energy usage. These are each example of the 'environment' portion of the model. The 'economic' part of the model is concerned with minimising costs, either capital investment or operating costs, or optimising another economic indicator, such as maximising return on investment.

The previous models have also had one flaw; they need to include a direct connection to the location of the potential energy sources. These models have all been conducted independently of the research on identifying potential renewable energy sources using GIS. When necessary, the models contain estimates related to the potential renewable energy source or sources. There needs to be more discussion of the origin of these numbers, which are often derived from other research and resources. These numbers may not reflect the reality of the situation, nor do they consider the location of these sources, which can impact the acceptability, costs, and timing of these resources on these models.

There is a need to seamlessly combine the exploration of potential sources with the modeling capability to provide a comprehensive model of both potential and optimisation.

## 2.11 Spatial Decision Support Systems (DSS)

Fundamental problems with specific solution methods are easily solved using GIS tools; however, when problems become complicated, more than simple logic may be needed for the solution. DSSs are developed to resolve more complex situations, and GIS is used as the DSS development platform to satisfy such needs (Rodriguez-Bachiller & Glasson, 2004).

Spatial decision-making problems do not always have to be structured or unstructured in the real world but may lie between these two extreme cases. These decisions are called semi-structured. Cooperation between computer-based systems and decision-makers is required in semi-structured decisions. Most real-life spatial decision problems are semi-structured (Malczewski, 1999). Spatial Decision Support Systems (SDSS) can cooperate and organise all activities and interests concerning the decision-maker's purpose. A system like this streamlines communication between ideas, evaluation of the outcomes, and decision-making. In other words, it assists in sharing information among decision-makers and considering the multiple criteria in a more organised and logical way (MacDonald & Faber, 1997).

The DSS developed in this thesis is a semi-structured decision support system. The model, developed in ArcView 3.3 model builder, allows some tasks to be programmed since the processes through the solutions are not repeated regularly, and each process stage differs from the other. However, user input is required to accomplish the remaining tasks. GIS can provide various analyses and visual demonstrations of cartographic data. Nevertheless, it does not assist the user in selecting suitable functions for a particular purpose or to interpret the results (Seffino et al., 1999). In considering spatial decision processes, a series of tasks is required to obtain results. First, decision-makers must construct the database relations and models, determine the appropriate modelling strategies, select the related data sets, and decide the flow of analyses. The results of analyses can be demonstrated, and solutions to the problems can be interpreted (Zhu et al., 1998). GIS can contribute to SDSS by generating different maps associated with choosing a given set of models and decision procedures (Seffino et al., 1999). However, additional modeling tools for more complex analytical methods can turn GIS into a well-developed SDSS (Silva & Eglese, 2000).

Many researchers have been trying to develop SDSS models using GIS. For example, Dragan *et al.* (2003) proposed an SDSS in Ethiopia. The study was based on determining new crop locations regarding their capacity to reduce soil erosion. GIS software IDRISI 32 was used to develop SDSS, and the direct involvement of local stakeholders was used to identify constraints and factors. Banai (2005) suggested an SDSS prototype based on land resource sustainability for urban development. Sikder (2009) proposed a knowledge-based decision support system to identify crop adaptability in each agroecological zone. A flexible interface was produced in GIS, which increased crop management and land use planning efficiency. Lejeune and Feltz (2008) developed a decision support tool in GIS to assess environmental and landscape constraints associated with wind farms.

## 2.12 GIS and Web-based Spatial Decision Support Systems

A GIS is a computer system with multiple integrated elements capable of assembling, storing, analysing, displaying geographically, and referencing information and systems (Hott et al., 2012). This has capabilities in facilitating decision-making in the form of geographically referenced data analysis (Kumar & Shekhar, 2014). In addition, site specificity is very important when using renewable energy sources like sun, wind, biomass, biogas, and water. The feasibility of their potential assessment and optimal use in rural areas depends on their availability. Joshi (2012) also reported that GIS could assist in deciding on the desired location, allowing decision-makers to focus on the real issues rather than trying to understand the data presented by GIS.

Using GIS in renewable energy helps to predict and obtain a high level of accuracy of the best location for placing the energy resources. GIS can save time and money determining where and how renewable energy sources should be exploited and used. GIS identifies areas with high potential for developing RES and regions with restrictions on their exploitation, such as environmentally or culturally sensitive areas. GIS will assist in improving how we deliver and produce energy and can support the development of cleaner, more innovative, and more eco-friendly methods of energy production.

In addition, GIS is more than just a tool used to handle geographic data in digital form, and display or create maps. GIS can be integrated with modeling, statistics, and analysis tools to carry out sophisticated tasks. Thus, it is natural to incorporate GIS with decision support systems (DSSs), commonly known as spatial decision support systems (SDSSs). Malczewski (1999) reported that SDSS is an interactive, computer-based system that supports users in achieving effective decision-making by solving semi-structured spatial problems. Further, Ascough et al., (2002) reported that there are two considerations of paramount importance for spatial multi-criteria decision analysis, namely the GIS component (that is, for the data acquisition, storage, retrieval, manipulation, and analysis capability) and MCDA analysis components (that is, aggregation of spatial data preferences into discrete decision alternatives) (Muataz, 2009).

The DSSs are special purpose tools that originated in the 1960s primarily in operational research and management science to address business problems. DSS is a comprehensive concept, and its definitions vary depending on the author's point of view (Druzdzel & Flynn, 1999). Gorry and Morton (1971) define a DSS as an "interactive computer-based system that helps decision-makers utilise data and models to solve unstructured problems." Finlay (1994) and others define a DSS as "a computer-based system that aids the process of decision-making". No matter the definition, DSS's basic idea is to provide a computer-based framework that integrates database management systems with analytical models and graphics to improve the decision-making process.

The SDSS is a class of computer systems in which the technologies of both GIS and DSS are applied to aid decision-makers with problems that have a spatial dimension (Walsh, 1992). A common motivation for making SDSS accessible online is to support group decision-making (Kingston et al., 2000; Zhu et al., 2001).

SDSS is mainly built upon a GIS coupled with modeling. There are several strategies and approaches for coupling environmental models with a GIS (Nyerges, 1993; Fedra, 1996), which can range from loose to tight coupling. A loose coupling is just the transfer of data between models and GIS, and it is based on two separate systems and generally separate data management. A tight coupling is one with integrated data management, in which GIS and models share the same database. The tightest of couplings is an embedded or integrated system in which modeling and data are embedded in a single manipulation framework (Crosbie, 1996; Fedra, 1996; Fedra & Kubat, 1993; Djokic & Maidment, 1993).

Noon and Daly (1996) have proposed a GIS-based Biomass Resource Assessment, Version One (BRAVO), described by the Tennessee Valley Authority to help determine the price of supplying wood fuel to any of its 12 coal-fired power facilities. In BRAVO, the GIS platform enables effective analysis of transportation networks, enabling precise estimation of hauling costs and distances. Another GIS-based DSS was developed to calculate the marginal cost of delivering wood chips to a specific location, given road network maps and maps of farm-gate prices and supplies of wood chips from short-rotation crops in Tennessee (Graham et al., 1997).

The SDSSs are potent tools. However, one of the issues is how to make the product easy to use and access. Malczewski (2007) defined the decision support system as the interactive, computer-based programme designed to support a user or group of people in increasingly effective and efficient decision-making while solving a semi-structured spatial decision problem. Since the emergence of the worldwide web in the mid-1990s, SDSS research has found a direction. Some of the most popular online geospatial applications, such as driving directions (e.g., Google Maps) combine features of Internet mapping and decision support. For further illustration, Sugumaran et al., (2004) developed a web based DSS that prioritises local watersheds indicating environmental sensitivity. Choi et al., (2002) developed a web based SDSS to assist with watershed hydrologic and water quality assessment for present and future land uses.

Overall, there have been minimal SDSS applications and even fewer web SDSSs. There is a great need to research how to integrate GIS, the internet, modeling, data reports, and databases to create a web SDSS.

## 2.13 Multi-Criteria Decision Analysis (MCDA)

Both individuals and groups of people face spatial decision-making in everyday life. Choosing a new development area, selecting a new residential area, or managing the infrastructure system requires spatial organisation. Most individual spatial decisions are made by considering heuristics or past experiences. However, more reliable, and analytical methods are needed for organisations to support spatial decision-making (Jankowski et al., 2001). The rationale of MCDM models is based on evaluation of multiple criteria to find a solution to problems with multiple alternatives. These alternatives can be evaluated by their performance characteristics, such as decision criteria (Jankowski et al., 2001). MCDM enables the decision-maker to evaluate alternatives according to conflicting and incommensurate criteria. A criterion is a generic term that may be constituted by both attributes and objectives. Therefore, MCDM can be classified into two groups: multi-attribute decision-making (MADM) and multi-objective decision-making (MODM) (Malczewski, 1999). In the MADM approach, each alternative is evaluated concerning various attributes, and final choices are made among potential alternatives.

On the other hand, MODM is based on the decision maker's objectives, which can be a statement about the system's desired state. Several different attributes represent objectives. In other words, MODM problems deal with the objectives which require establishing specific relationships between attributes of the alternatives (Malczewski, 1999).

Pohekar and Ramachandran (2004) reported that energy planning using multi-criteria analysis had attracted decision-makers' attention for a long time, and the method increasingly provides solutions for complex energy management problems. As the decision-makers are required to choose among quantifiables or non-quantifiables, the multiple criteria decision-making method can deal with processes of decisions in the presence of multiple objectives. In most cases, different decision-makers are involved in the process. Each group brings different criteria and points of view, which must be resolved within a framework of understanding and mutual compromise (Pohekar & Ramachandran, 2004).

Nigim et al. (2004) noted that various tools are currently used to facilitate decision-making in selecting renewable energy technologies. These tools can be used during a pre-feasibility study on prioritising renewable energy technologies through objective ranking procedures. As a result, finding the optimum solution based on several aspects and considering the stakeholders' expectations requires recognising and selecting options. Every decision is made in a decision environment, which is the set of facts, options, standards, and preferences that are available when the decision needs to be made (Nigim et al., 2004). For this reason, the multi-criteria conceptualisation and frameworks for planning and prioritisation of energy supply alternatives for isolated areas, including models that assess environmental impacts, have been used.

Although extensive vital electrification has been achieved in the developing world by expanding national grids to rural areas, millions of people, especially those in poor rural areas, still have no access to modern energy services. Energy supply to the rural poor in developing countries is a complex activity that transcends the simple selection of the best technology (Cherni et al., 2007).

In approaching the planning of energy provision, assessment methods often emphasise only a few aspects of the rural energy problem. Hence, multi-criteria analysis is helpful as the prioritisation of electricity generation options is a multi-faceted problem, requiring consideration of both qualitative and quantitative factors, particularly those utilising renewable energy technologies faced with numerous obstacles (Polatidis and Haralambopoulos, 2002; Cherni et al., 2007).

## SUMMARY

Renewable energy technologies are increasingly being adopted substantially in South Africa. It is assumed that strengthening the use of these clean energy resources can meet new international environmental requirements. This will provide a self-sufficient domestic and rural energy supply, especially as South Africa is among the most polluted countries in the world. Renewable energy sources are characterised by decentralised energy production (Beatley, 2000). Their utilisation must consider factors such as technical potential, environmental constraints, and incentives for investment (BMU, 1999; Boyle, 1996; ECDGE, 1998; Voivontas et al., 1998). Building a decision support system based on these factors would help assess exploiting renewable energy sources for optimal use and specific location per demand. As a result, a growing number of regional problems driven by the social, economic, cultural, sustainability, and environmental forces require the assistance of spatial decision support systems for renewable energy planning in enhancing the variety of energy management solutions (Bone & Dragićević, 2009; Barkan et al., 2006; Jankowski et al., 2006; Nyerges et al., 2006; Jankowski, 2000 and Jankowski et al., 1996).

However, SDSS tools are greatly needed when problems emerge from adopting renewable energy sources where decision-makers need help to identify essential elements and establish relevant theories and potentials for the problems they are trying to solve.

Since most of the population in the region living in rural areas is cut off from the central grid-connection power distribution and access, they would significantly benefit from the maturation of technologies that exploit renewable energy resources of the sun, wind, biomass, and flowing water. This research aims to assess, simulate, analyse and test the renewable energy potentials as a culturally practical alternative energy resource suitable for everyday village use in the Vhembe District Municipality.

Many countries worldwide have integrated RES in their future energy plans to reduce the negative impacts of fossil fuel consumption on the environment. However, the use of RES is essential in its relationship to the geographic locations and availability of these facilities. This research aims to develop a geographic information system-based methodology for evaluating and assessing these systems' availability and optimal usage. In the application of the decision support system to determine the potential and maximise the energy supply, a single or hybrid energy system will be considered. All the criteria and feasibilities (i.e., environment, technical, social, economy, sustainability, and regulatory) will be identified through environmental objectives and economic feasibility through South Africa and Limpopo Province legislation, previous studies, and interviews with the municipality. The individual or combined energy potential will be calculated using the tool. This renewable energy potentials will be determined through their performance with indexed maps, sites, and availability for energy generation. Finally, maps of priority and potential renewable energy sources will be overlaid to identify suitable optimal energy systems. The proposed research methodology will be applied to a case study area of Vhembe District Municipality in Limpopo Province.

The literature review found very few studies conducted to model, assess, simulate, analyse, and optimise the use of renewable energy resources in rural areas.

Few GIS applications are related to renewable energy potentials; however, these studies focus on individual energy potentials, specifically solar, biomass, bioenergy, wind, and water as energy supplies. For example, food waste resources have been identified and mapped for recycling. As a result, there needs to be more investigation into utilising all the renewable resources available to determine the optimal energy supply that can be implemented using them.

This study assessed all four municipalities within Vhembe District Municipalities to obtain the overall renewable energy potential map. A spatial decision support tool was developed in a GIS environment to identify the feasible locations for all available renewable energy potentials and development to assist decision-makers in facilitating the decision process for selection.

# CHAPTER 3: Solar Energy Assessment, Estimation, and Modelling

## 3.1 Solar Radiation Estimations using Territorial Climatological Measurements

**Article 1:** Solar Radiation Estimations using the Territorial Climatological Measurements in Vhembe District, Limpopo Province for Solar Energy Potential Estimation and Use

This paper assesses, estimates, and models solar energy potential using climatic and territorial measurements. The data measurements of the global solar radiation used in the area were obtained directly from locations where installed weather stations were placed. The data was taken from extra-terrestrial radiation and metrology data using the sunshine and cloudiness as empirical data. As a result, the thematic maps were generated from GIS to access the availability and variation of global solar radiation. Consequently, the solar energy potentials were obtained from specific locations where the data included temperature, relative humidity, rainfall, and hourly sunshine details.

The application of GIS as a tool in solar energy resources and potentials was essential to the site selection of the solar plants, especially for the environmental and economic feasibility criteria in the review of the existing energy policies, strategies, and planning tools for energy potentials. The solar energy assessment informed and identified the gaps in social services, economic activities, and planned energy services set in the government's policy statements/documents. As a result, the solar energy potential was quantified, and potential maps were generated to determine the solar radiation potential and geographic conditions that yield annual energy potential and renewable energy policies to influence economic potential. Hence the comprehensive site selection for the solar generation plants should be followed by the environmental and economic feasibility criteria as demonstrated by the conference paper presented at the IEEE PowerAfrica in Nigeria 2019 and the article published in the ASTEJ journal. The published article constituted the published conference paper in the journal as per the thesis requirements and content indicated in the following chapter.

# Solar Radiation Estimations Using the Territorial Climatological Measurements in Vhembe District, Limpopo Province for Solar Energy Potential Estimation and Use

Clement Matasane and Mohamed Tariq Kahn
Cape Peninsula University of Technology (CPUT)
Faculty of Engineering and Built Environment
Electrical and Electronic Engineering Department
Symphony Way, Bellville Campus
Bellville, South Africa
matasanec@cput.ac.za and KhanT@cput.ac.za

***Abstract*—Determining the solar radiation for the use of energy generation involves a number of procedures, estimations and calculations using the climatological weather data measurements. The case study was conducted in the Vhembe District area through the nine installed Weather Stations (WS). The analysis determines the minimum and maximum solar radiation equations associated with the local climate patterns in accommodating the theoretical bases and its time period changes. The paper contributes to the main project objectives on renewable (i.e. solar, wind, biomass/biogas and hydro) energy assessment for their potentials and generating at small/ micro scale in the district. These parameters are very important in estimating the solar energy radiation to the area using its extraterrestrial solar radiation per day/ weekly/ monthly and annual periods. The metrology estimations through graphical representations were performed. These provided calculations in which territorial solar energy was determined through climatic conditions and analysis found to be usable.**

***Index Terms*-- Climatological Measurements, Extraterrestrial Radiation, Solar Energy, Sunshine Data, Territorial Measurements.**

## I. INTRODUCTION

Solar energy applications play a major role in health, acro and agriculture, civil engineering and environment for their performance to support the energy demands within the field [1]. The current developments towards sustainable energy savings and generation using the solar photovoltaic (PV) units have accelerated the growth process and investment in the field [2]. In Limpopo Province, there is adequate sunlight which can be more utilized for solar energy applications. It is therefore important to harvest and store this natural resource in view of finding a solution to energy shortage and environmental degradation that the province is facing. The province has five districts which many of its communities still live without grid-connected electricity. It is of the view that solar energy systems are being considered as the most cost-effective and economical power systems in providing off-grid electricity generation to rural areas in the province.

In estimating the renewable energy (RE) potentials using the geographical and climatological data, need thorough calculations of solar, wind, biomass/biogas and hydro energy potentials in the specified location. Hence the amount of solar energy per location is important. The estimation of current global solar radiation in the Vhembe District area was required. The global solar radiation can be obtained in many databases and for this study, the International Renewable Energy Agency (IRENA) Global Solar Data Radiation for the Limpopo Province was used.

It is very important to know where renewable energy sources come from as almost all their sources originate entirely from the sun [3]. Thus, the sun's arrays that reach the atmosphere are subjected to a number of factors including array absorption, scattering, reflection and transmission through the atmosphere, before reaching the earth's surface or location of interest. This array is classified into three categories: - diffused, reflected and direct solar radiation as representing the solar energy from the sun. Solar radiation data that reaches the ground level is of importance into many wide ranges of applications for meteorology, engineering, environmental sciences, agricultural hydrology and sciences, soil sciences and its physics. In addition, these include the modelling and estimation of crops and crop evapotranspiration, special health sectors and medicine, and other researches in the natural sciences [4], [5].

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Focusing on South Africa and looking into energy systems and their uses, there are currently many projects being developed. The importance of utilizing solar energy schemes in most parts of Limpopo Province has increased. Independently, increasing and promoting awareness on issues towards climate change and factors regarding the community is one of the major economic challenges [6] – [8]. This has been realized as the potential and important opportunity in directing the energy security and carrying out of one the research niche area within the environmental Millennium Development Goals (MDG) on energy [9].

The solar radiation data measured provide information on how much solar energy is reflected on the surface during the specific time period (i.e. hourly, daily, monthly and yearly) at the specific position. These measured data are of importance for effective solar energy research for utilization and providing energy through natural resources such as photosynthesis [2]. In modern energy engineering, there are many cases involving equipment subjected to solar radiation [5], [10]. This includes technology equipment such as street lights, traffic lights, remote control gates, public messages and notices and other solar energy supplied units installed within the residential district without proper grid-connected electricity supplies. This equipment is provided by the sunlight power source through radiation at defined energy absorption which causes different significant. The need for using the radiation data within the Vhembe District allows determining the solar radiation parameters connected to the power needed for solar energy utilization.

It is noted that solar energy forms part of the ultraviolet intensity spectrum, defined by the physical wave solar constant (K). This is the electromagnetic constant which flows through a unit area (A) by the solar array directly to the earth surface distance from the sun. As the results, to measure the necessary solar energy, it is important to recognize the duration time (T) of solar array path through the aura to the specified destination location [11].

This work introduces a mathematical and estimation radiation model and calculations developed for the Vhembe District in designing the solar energy schemes as per the radiation data found through the installed meteorological stations. The solar energy is determined and analyzed in different geographical locations that enables the parameters in calculations for any location on an hourly basis or daily. As the results, to determine the possibilities with radiation measurement in planning solar energy systems, a specific amount of radiation will be used.

Consequently, mathematical solar energy model used for data prediction provides a comprehensive solar energy potential in Vhembe District in hourly, daily and monthly solar radiation on location determined. The main objectives of the present study are to determine daily, monthly-average global and diffuse radiation values for the Vhembe District as shown in Fig. 1. This estimated energy forms part of the sub-energy potentials to be obtained from solar, wind, biomass/biogas and hydro energy estimation in estimating the optimal energy generation within the areas. This will help in geo-referral every energy estimation information within the district. The area is situated an 22.7696° S Latitude, 29.9741° E 25 Longitude of the Limpopo Province and at an altitude of 250m above mean sea level.

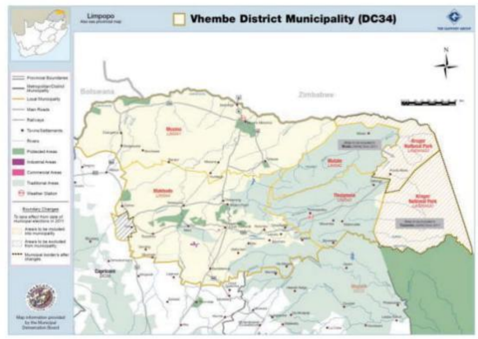


Fig.1 Vhembe District Area with all the nine installed weather stations.

According to Mulaudzi [12], there is still high unemployment rate and people still uses traditional energy methods in most rural areas. In most areas of the district, people are still disadvantage as they can't afford grid-connected electricity and using most of renewable resources such as traditional biomass, encroachments, paraffin and gas as quality of life still depends on natural resources. The district has 14 main commodities as shown in Table I. The majority of the community depends on farming as their economic sustainability. These are commodities which smallholder farmers depend on improving their livelihoods and creation of employment to the communities [2], [13].

TABLE I. NUMBER OF SMALLHOLDER FARMERS IN VHEMBE DISTRICT [2]

| Commodities | | No. of Smallholder farmers |
|---|---|---|
| a) | Backyard gardens | 644 |
| b) | Banana | 409 |
| c) | Citrus | 16 |
| d) | Fish | 81 |
| e) | Garlic | 39 |
| f) | Guava | 128 |
| g) | Litchi | 4 |
| h) | Livestock's (cattle, sheep, pigs and goats) | 15 646 |
| i) | Macadamia | 512 |
| j) | Mango | 758 |
| k) | Piggery | 6 |
| l) | Poultry | 992 |
| m) | Tomato | 2015 |
| n) | Vegetables gardens | 2300 |
| **TOTAL** | | **23 636** |

With such commodities, an estimation of waste to bio-energy plant could be constructed to enable the communities to use their waste materials and reverse it into a valuable product that can benefit them. This will be utilized in seeing their energy needs, or a marketable product as the source of income in supplying waste to the bio-energy plant that could be grown inside their region. This will enable the communities to have a cleaner, healthier environment and potential job creation and access to some improved form of energy that improves their living standards. The same application with biomass, wind and hydro energy resources are going to be assessed.

It should be noted that the measurements obtained for the solar radiation and humidity climate weather data through the instruments used are often subject to stability error function as exposed to heat transfer within the atmosphere. This heat transfer, it is commonly seen as the drift as little as 10% of the determined values [14]. In addition, there is relatively 1% humidity loss on the instruments per month [15]. According to [16], there are many available studies made about the global solar radiation models. This includes available models in estimating the daily, weekly, monthly and annual radiation used for solar energy estimation purposes [17].

## II. Materials Analysis and Methods

There are many solar radiation databases available for most parts of the countries around the world. As the results, several empirical models have been developed, estimated and calculated based on the available sunshine per hour/ daily/ weekly, monthly and annually. The NASA, SOLPOS and Google Map was applied during the solar estimation of the study area. Measurements were remotely captured throughout one complete year. The data acquisition (DAQ) system was used to obtain data from the nine Weather Stations (WS) used during the data collection (i.e. Hanglip, Shefeera, Tsianda, Thohoyandou WO, Dzanani Biaba Agric, Mphefu, Joubertstroom Plantation, Vondo - Bos and Tshivhasie Tea Venda). This was to determine the annual weather changes and patterns for the ranges on the annual session.

It was difficult to measure solar radiation in many locations due to cost of equipment to be used, maintenance, and calibrations to obtain accurate values. Hence, the South African Weather Stations (SAWS) meteorological weather data was used in all the nine weather stations (WS) been installed. As the results, within reference to the measurements obtained, the data was used to determine the solar energy potential for the Vhembe District at specified locations to evaluate its amount for power generation. This data was remotely captured and used to estimate the potential solar energy per location for power generation by photovoltaic system modules. In addition, the efficiency and error calculations were considered as was difficult in measuring the solar radiation at geographical location due other factors, including absorbed or reflected by the atmosphere.

Following the data obtained, available renewable energy resources within the Vhembe District was of important and the peoples' quality of life as purpose in using the solar energy to meet their energy demands.

Furthermore, the desirable amount solar energy was measured during the allowable day time duration (that is from 06:00 – 19:00) for the whole year per locations during 24hr time interval. With reference to the measurements, it was used to determine the variations for the minimum and maximum coefficients through the solar radiation calculations using the software analysis. As the result, equation 1 to 7 were acknowledged in design and calculations of the solar radiation energy and presented by the graphical responses in Fig. 2 to Fig. 6 for the irradiance measurements.

Estimation of the solar radiation energy is a critical measurement in designing the solar energy system or devices. However, the estimation and measurement is not easily determined due to the cost and techniques required to used. As the results, there is a need to establish the theoretical methods for estimating solar radiation, such as the empirical relationships using commonly measured climatological data measured at the specific area [23], [24]. The Vhembe District has a very complex topology, hill and mountainous zone area due to its location and extensive territory, hence different climate data were determined through the nine installed weather stations.

## III. Basic Solar Irradiance Measurement

The radiometer is an instrument for measuring irradiance in equal amounts of solar energy at specified wavelength range measured [18]. The great care was considered in choosing a site location with reference to the determined climatological measurements within the area of interest during the day or in the year [19]. In addition, it was understandable that new models and techniques exists and being developed in improving the measurement techniques for estimating the solar radiation energy with accurate, readable available meteorological parameters, hence the consideration for the solar radiation on horizontal surfaces and tilted surface forms part of the estimations [20]. Table II shows important parameters in measuring the solar radiation at different location. These was used to assess the availability of solar radiation at specified location.

TABLE II. Parameters Needed for Solar Radiation Measurements

| **Parameters** | **Units** |
|---|---|
| Global radiation | G ($W/m^2$) |
| Diffuse radiation | $G_d$ ($W/m^2$) |
| Beam radiation | $G_n$ ($W/m^2$) |
| Sunshine hours | $\sigma$ (hrs) |
| Maximum and minimum temperature | $T_{min}$ and $T_{max}$ (°C) |
| Humidity | H (%) |
| Pressure | P (Pa) |
| Visibility | F (m) |
| Wind speed and directions | V(m/s); N,W,E,S |
| Air mass | $\rho$(kg/s) |

In Fig. 2 to Fig. 6, shows the monthly graphical metrological analysis of the area for maximum and minimum temperature, length of the day (sunshine hours), and the horizon yield throughout the year together with the direct solar radiation measurement. These measurements were acquired through the duration of the day inside the district to get a micro solar system for the community expectation and energy demands.

It was noticed that the highest values of the solar insolation are during the summer months (Jan to Apr and Sept to Dec) and the lowest values are during the winter months (May, Jun, Jul, and Aug) as applies in accordance with duration of the day during that time for the season.

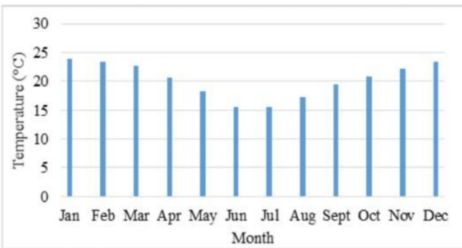


Fig.2 The monthly temperature measurement (Average - 20 °C)

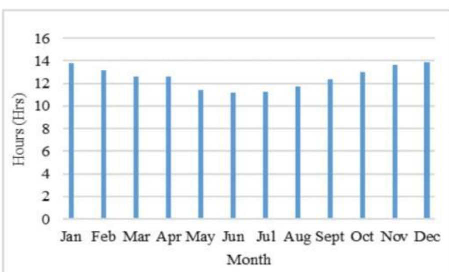


Fig.3 The monthly length of the day measured (Average - 12.5Hrs)

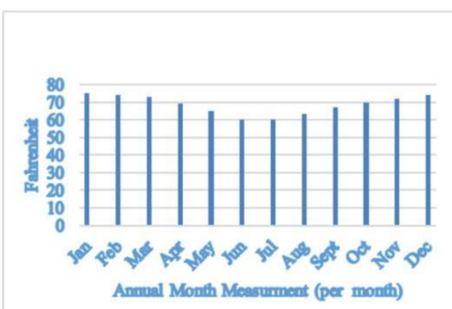


Fig.4 The annual temperature measurement for Thohoyandou region in Fahrenheit (Average - 68.5 F)

As the graphical analysis demonstrates, the irradiance and temperatures varies depending on season. It is noticed that the radiation is high in summer time. As the results, the annual meteorological data gathered, will make possible for the PV performance analysis for power generation. In addition, the minimum and maximum radiation was obtained during the summer and winter periods as it was uniform throughout all the months, as demonstrates by the lowest and highest measurements.

The determined values are useful for the design and estimation of the total performance of solar energy system to be installed. This will determine the optimal figures to be used in estimating the available solar energy for generation in matching its design concept.

The area is known for its abundance in radiation and determined available solar resources with great influence on the design, configuration, and the cost of power system developed. It was noticed that the highest values of the solar insolation are during the summer months (Jan to Apr and Sept to Dec) and the lowest values are during the winter months (May, Jun, Jul, and Aug) as demonstrated by Fig. 2 to Fig. 6.

Taking one of the region, the annual daily horizontal solar radiation for the Thohoyandou Region, is 5.40kWh/m$^2$/day as measured from NASA, using the RETScreen software as shown in Fig. 5.

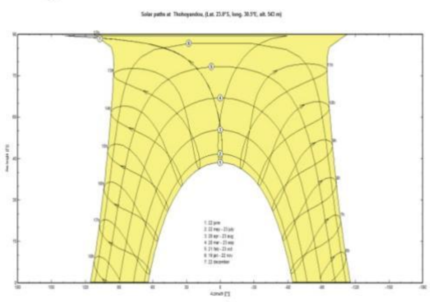

Fig.5 The horizon yield of Thohoyandou solar radiation

These estimates and weather patterns have been obtained and analyzed through weather station in the Vhembe District installed around the area.

Using the SAWS WS measurements which are represented by Fig. 2 to Fig. 6 and Table 1 – 2 that shows the average length of the day and the temperature responses that the obtained solar radiation was only available from 06:00am to 06:00pm per day during the whole month as determined the by the Earth and Sun orbiting throughout the year. These months have been used as they represent the minimum and maximum solar energy level during the for the solar radiation measurements.

## IV. Basic Solar Radiation Intensity

The parameters affecting the solar radiation intensity within the atmospheric region are of importance in solar energy as others arrays are reflected throughout the air [21].

That is, the spectrum of the radiation emitted by the sun is about the energy in the ultra-violet region as the solar radiation beam (i.e. constant ($I_0$)) passes through the atmosphere when the sun is at its mean distance from the Earth [18]. This value is

$$I_0 = 1.37 \pm 0.02\text{kW/m}^2 \quad (1)$$

The variances in the space between the sun and the world due to the Earth's orbiting cause the real strength of solar radiation outside the atmosphere to differentiate from $I_0$ by a few percent to take into account these variations by mean factor, F in Degree Celsius.

$$F = 1 - 0.0335 \sin 360(n_d - 94)/365 \quad (2)$$

Where $n_d$ is specific day of the year (i.e. $n_d = 1$ for month of January….and $n_d = 365$ for month of December); the argument of the sine function is in degrees. All the values of solar radiation intensity given below, which are for the sun at its mean distance from the Earth, must be multiplied by F to obtain the actual values on day $n_d$. During, January, as the weather is clear, sun closer to the Earth, the solar radiation is 3% greater than the average and in July, when the Earth is farthest from the sun, the solar radiation is 3% less than the average.

Using the SOLPOS system to calculate the sun intensity from given location at specific day and time, gives the extraterrestrial direct normal solar irradiance (W/m$^2$) of given range per day within a month for the period of 1950 – 2050 with accuracy of 0.01°C. These measurements were obtained using the web-based system calculating the solar ration. The amount of solar radiation measured was of both highly received within time and location variables. Fig. 6, shows the radiation energy tends during the January, June, July and December month.

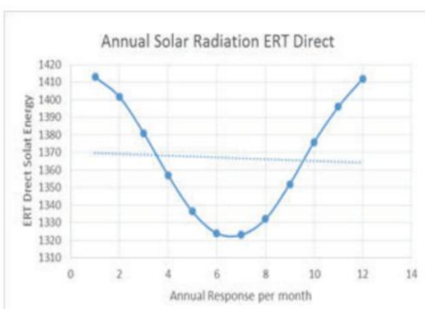


Fig.6 Energy trends for Solar Radiation in Vhembe District

## V. Prediction Model and Determination of Solar Energy Radiation at Specific Area and Particular Time

The site selection has a direct impact on the potential renewable energy systems (RES) projects in many different ways including technical, economic and environmental aspects. However, one of the critical role in PV power plants is the inconsistency and variability of solar irradiation which can be geographically dissimilar from one location to another [22]. To measure the specific amount of solar radiation at specific area and particular time, it is important to define angle of inclination by cos(δ) of solar arrays to perpendicular of the earth by considered area of interest, cos(θ) and expressed by total amount of watts per meters square (W/m$^2$) and the joules per meter squares (J/m$^2$) [11].

In measuring the solar radiation, the territorial solar irradiation ($E_{ss}$) and the global solar irradiation ($E_{ET}$) are considered. Hence, the total solar energy ($E_s$) above the atmospheric level is equal to the total atmospheric solar energy at sea level multiplied by the length of day (N) per change of temperature (T) throughout the year as determined by equation 3. The latitude (L) and angle of declination (δ) by the sunlight must also considered during the surface of absorption.

$$E_s = (I_o + 1) + 0.34 \cos\frac{2\pi N}{365} \times L \quad (3)$$

Where the Io is the solar constant = 1,367W/m$^2$ (is the eextraterrestrial radiation as the earth orbits around the sun) and N is the number of the day for solar absorption, 0.34 being the constant coefficient of solar irradiance at atmospheric level and L is the length of the day being calculated by equation 4 and the $\cos\frac{2\pi N}{365}$ is the angle of declination by the sun during the day through per year.

The length of day was calculated by: -

$$L = \frac{2}{15}\cos^{-1}(-\tan L \times \tan\delta) \quad (4)$$

This was determined by the length of day per the solar decline angle (δ) as calculated by Equation 5.

$$\delta = 23.45 \sin\frac{(284+N)}{365} \quad (5)$$

In normal circumstances for the Vhembe Region weather measurements, the minimum length was 11.2hrs and the maximum length of day was 13.9hrs [2]. Therefore, the solar energy ($E_s$) for the minimum and maximum was determined by equation 6 and 7.

$$E_{s(\min)} = (I_0 + 1) + 3{,}808 \cos\frac{2N}{365} \quad (6)$$

$$E_{s(\max)} = (I_0 + 1) + 4{,}726 \cos\frac{2N}{365} \quad (7)$$

## VI. Conclusions

To obtain the suitable optimal and potential use of PV radiation, it is essential to investigate the location suitability for the purpose in order to maximize the solar energy received and the power generated at the selected location. In this paper the metrological estimations, graphics and formulae were attempted in order to determine the behaviour of the Vhembe District climatic conditions as one of the rural areas of interest in deploying the renewable energy technologies such as solar system. As the result, the analysis demonstrates that the required solar radiation values for the potential use in the area are estimated by the temperatures commonly measured by the installed weather stations around the Vhembe District.

Furthermore, intensive research studies within specific locations should be carried to specially identify and determine its environment issues associated with the location and its natural resources to determine potential energy sources available for the community use.

It is observed that active role of solar energy systems has environmental impact compared to other sources. These solar energy technologies should be increasingly introduced within the rural areas taking into account the suitability and energy potential of the area.

In summary, solar energy offers many advantageous over other alternative energy sources and as shown in the paper, there are simple principle of solar heat energy that can be applied in some various applications. However, it is noted that solar energy has its own drawbacks or limitations like high initial cost, dependence on weather and challenges in energy storage. As the results, South African Government is increasingly introducing initiatives with plans in provide subsidizing the programmes to increase an effort in promoting solar energy use in the rural areas.

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## 3.2 Solar Energy Potentials Using Climate Data and Local Environmental Conditions

**Article 2:** Solar Energy Assessment, Estimation, and Modelling Using Climate Data and Local Environmental Conditions

This paper is an extension of work initially presented at the 2019 IEEE PES/IAS Power Africa Conference in Abuja, Nigeria. This article provides an extension and detailed result to determine the daily, monthly, annual, and solar potential and radiation within the Vhembe District. This paper estimates the energy potential as part of the sub-energy potentials obtained from wind, biomass/biogas, and hydro-energy for optimal energy generation in the area. This paper provides comprehensive data and GIS maps obtained and MATLAB analysis during the study analysis.

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# Solar Energy Assessment, Estimation, and Modelling using Climate Data and Local Environmental Conditions

Clement Matasane[1,*], Mohamed Tariq Kahn [2]

[1]Cape Peninsula University of Technology (CPUT), Electrical and Electronic Engineering Department, Symphony Way, Bellville Campus, Bellville, 7925, South Africa

[2]Cape Peninsula University of Technology (CPUT), Research Chair: Energy, Director: Energy Institute, Head: Centre for Distributed Power and Electronic Systems, Head: Centre for Research in Power Systems, Symphony Way, Bellville Campus, Bellville, 7925, South Africa

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ABSTRACT

*On Renewable Energy (RE), this field covers the most significant share of the world energy demand and challenges on the expensive measurement and maintenance equipment to be used. In all studies and designs, global solar radiation (GSR) measurements require assessment, estimation, and models to be applied together with the environment and meteorological data on installing stations at the specific location. These meteorology stations provide measured data throughout the year/ annually or at specified periods, depending on the site of interest. This study includes assessment and estimations of the solar radiation at the Vhembe District using the geographical data measured daily, monthly, and throughout a year in the area. It provides variables such as the geographical maps of the solar availability at a minimum and maximum temperatures obtained during the annual analyses. Determining the solar radiation at a specific location for energy generation involves several procedures, estimations, and calculations using the climatological weather data measurements through MATLAB simulations. In addition, the Geographical Remote Sensing (RS) and Mappings, and Spreadsheet Graph Analytics, were applied to the measured data from the nine installed Weather Stations (WS) in the Vhembe District area was used. The analysis determines the minimum and maximum solar radiation equations associated with the local climate patterns in accommodating the theoretical bases and period changes. The paper contributes to the main project objectives on renewable energy assessment for potentials and generation at a micro/small scale in the district. These parameters are fundamental in estimating and determining the potential solar energy radiation using its extraterrestrial solar radiation per day/ weekly/ monthly. Annual periods towards methods to develop micro/small energy projects for rural and urban communities for domestic and commercial use. As a result, the meteorology analysis is being presented in this study.*

## 1. Introduction

This paper is an extension of work initially presented at the 2019 IEEE PES/IAS Power Africa Conference held in Abuja, Nigeria [1]. This article provides an extension and detailed result to determine the daily, monthly, annual, and solar potential and radiation within the Vhembe District. This demonstrates the estimating of the energy potential as part of the sub-energy potentials obtained from the wind, biomass/biogas, and hydro energy for the optimal energy generation in the area.

Solar energy applications play a significant role in health, agriculture, civil engineering, and the environment for their execution to support the energy demands within the domain [1], [3]. Hence, evaluating the solar energy potential at any specified location requires accurate solar radiation information. The sunshine duration from the most common variable for predicting global solar radiation (GSR), so sunshine duration can be easily calculated, reliable, and widely used. In increase, solar radiation is

*Clement Matasane, CPUT, Symphony Way, Bellville, 7925, South Africa, +27(021) 4603383 & matasanec@cput.ac.za

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the primary root of energy and varies per amount of energy received at different locations [2], [28], [30]. The current developments towards sustainable energy savings and generation using the solar photovoltaic (PV) units have accelerated the maturation process and investment in the area [3]-[5], [11], [29]. In the Limpopo Province (coordinates as 22°50 "22. 08" S and 30°18 "36" E), there is adequate sunlight, which can be more utilized for solar energy applications as shown in Figure 1 to Figure 3. The images were obtained from the Global Solar Atlas developed by the Energy Sector Management Assistance Program (ESMAP) and SOLARIS supported by the World Bank. It is thus essential to harvest and store this natural resource to find a solution to energy shortages and environmental degradation at the state. It is of the view that solar energy systems are considered the most cost-effective and economic power systems in providing off-grid electricity generation in rural areas in the province.

Estimating the renewable energy (RE) potentials using geographical and climatological data requires thorough calculations per specified location. Hence the quantity of solar energy per location is essential, as shown aside from the direct average irradiation, global horizontal irradiation, and potential photovoltaic power for the region from Figure 1 to Figure 3.

More geographical, climatic, and analysis data were added to present conditions and their placement in this paper. Figure 1 to Figure 3 illustrates the available solar map available in the provinces, demonstrating that in the region of Limpopo Province, especially in upper streams, there is enough radiation in considerations for the development of solar energy projects from a small scale to large scale. The accessibility of the radiation in those fields can be demonstrated to last around twelve hours every day as it is one of the hottest areas in the state.

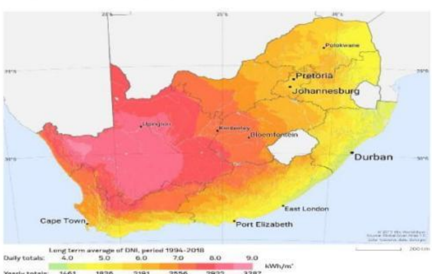


Figure 1. The direct average irradiation through the region (© Global Solar Atlas, 2020)

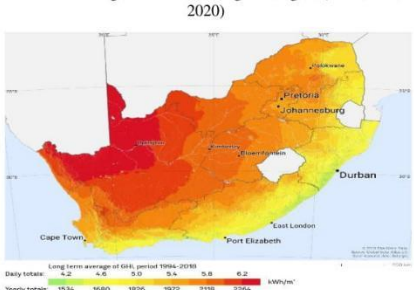


Figure 2. The global horizontal irradiation through the region (© Global Solar Atlas, 2020)

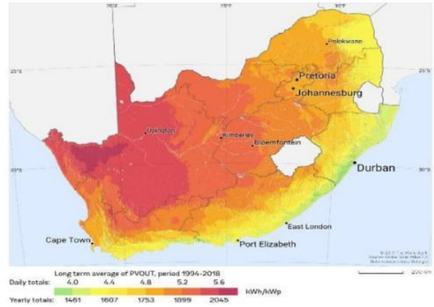


Figure 3. The potential photovoltaic energy for the region (© Global solar Atlas, 2020)

Every country has different solar radiation data but needs other techniques and measurements to determine a specific location. It can be touched on that there are various models produced to determine available solar radiation based on the sunshine hours. In South Africa, mainly, it plays a significant part in renewable energy systems and applications such as in health systems, agriculture, and farming, construction, and housing for domestic and industrial use [1], [28] as it is regarded as the most efficient and economical alternative resource and unused abundant sunshine available throughout the year.

It is essential to know where renewable energy sources come from, as almost all sources originate entirely from the sun [5]. Therefore, the sun's arrays that get into the atmosphere are subjected to several elements, including array absorption, scattering, reflection, and transmission through the atmosphere, before arriving at the earth's surface or location of interest. This array is separated into three categories: - diffused, reflected, and direct solar radiation representing the solar energy from the sunlight. Solar radiation data that arrives at the ground level is essential for many wide ranges of applications for meteorology, applied science, environmental sciences, agricultural hydrology and sciences, soil sciences, and physics. In summation, these include the modeling and estimation of crops and crop evapotranspiration, particular health sectors and medicine, and other research in the natural sciences [6], [7], [24].

Many projects are currently being developed, focusing on South Africa and looking into energy systems and their habits. The importance of using solar energy schemes in most parts of Limpopo Province has increased. Independently, improving and raising awareness on issues towards climate change and factors regarding the residential area is one of the significant economic challenges [8]–[10], [27]. This has been understood as the potential importance and opportunity in addressing energy security and carrying out of one the research niche area within the environmental Millennium Development Goals (MDG) on energy [11], [26].

The solar radiation data measured provide information on how much solar energy is reflected along the airfoil during the specific period (i.e., hourly, daily, monthly, and yearly) at the particular position. These measured data are of importance for efficient solar energy research for utilization and providing energy through natural resources such as photosynthesis [3]-[5]. In modern energy engineering, many cases are calling for equipment subjected to solar radiation [6], [7], [11]. This includes technology equipment such as street lights, traffic lights, remote control gates, public messages and notices, and other solar energy-supplied units installed in the residential district without proper grid-connected electricity supplies. The sunlight power source furnishes this equipment through radiation at defined energy absorption, which causes different significance. Using the radiation data within the Vhembe District allows determining the solar radiation parameters connected to the power needed for solar energy use.

Solar energy forms part of the ultraviolet intensity spectrum, determined by the physical wave solar constant (K). This electromagnetic constant flows through a unit area (A) by the solar array directly to the earth's surface distance from the sun. As a result, to measure the necessary solar energy, it is essential to know the duration time (T) of the solar array path through the aura to the specified destination location [12]. In addition, the amount of incoming solar radiation on the Earths' surface is the measurable amount during the minimum (Tmin). The maximum (Tmax) temperature (that is, in Degree Celsius) at relatively on a daily average of sunshine per hour (hrs); this requires a validated model to be used [12], [26]. Hence the data predictions at the specified location are of importance for the estimation and design in energy conversion for domestic employment industrial and commercial applications [13], [27].

This study introduces a mathematical and estimation radiation model and calculations developed for the Vhembe District to design solar energy strategies as per the radiation data found through the installed meteorological stations. The solar energy is specified and analysed in different geographical locations that enable the parameters in calculations for any positioning on an hourly basis or day by day. As a result, a specific amount of radiation will be employed to determine the possibilities with radiation measurement in planning solar energy systems.

Thus, the mathematical solar energy model used for data prediction provides a vast solar energy potential in the Vhembe District in hourly, daily, and monthly solar radiation on the location determined. Once more, the Vhembe District has a very complex topology, hill mountainous zone area due to its position, and extensive territory with plantations and vegetation, as shown in Figure 4 to Figure 8. As a result, climate data are critical throughout the year due to the location's land cover and weather patterns.

Figure 4. The Thathe Forestry and plantation

Figure 5. The Tshakuma Mango plantation

Figure 6. The Levubu banana plantation

Figure 7. The Elim litchis plantation

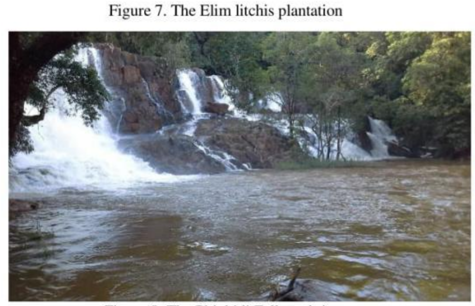

Figure 8. The Phiphidi Falls and river

These plantations (including corn, wheat, and sugar cane) furnish the wood wastes through organic materials that can be applied directly or converted into biofuels or bugs to be burned as fuels to generate energy. Besides, with the availability of the upstream and downstream rivers, there are opportunities that micro/small hydropower systems can be developed to assist the small farmers within the area for the irrigation and plantations, as shown in Figure 8.

In all four districts, people live under a very disadvantageous eco-system and environment, such as limited access to grid-connected electricity and using most natural resources such as traditional biomass, encroachments, paraffin, etc., and gas their energy resources. Also, the district has 14 primary commodities, as shown in Table 1. The majority of the community depends on farming as their economic sustainability, improving their livelihoods, and creation of employment for the rural communities [3], [14], [24].

Table 1. Type of agricultural farmers in the district [2]

| | Commodities | No. of Smallholder farmers |
|---|---|---|
| a) | Backyard gardens | 644 |
| b) | Banana | 409 |
| c) | Citrus | 16 |
| d) | Fish | 81 |
| e) | Garlic | 39 |
| f) | Guava | 128 |
| g) | Litchi | 4 |
| h) | Livestock's | 15 652 |
| i) | Macadamia | 512 |
| j) | Mango | 758 |
| k) | Poultry | 992 |
| l) | Tomato | 2015 |
| m) | Vegetable gardens | 2300 |
| | **TOTAL** | **23 636** |

With such commodities, an estimation of waste to bio-energy plants could be manufactured to enable the communities to use their waste materials and turn them into a valuable product that can gain them. This will be utilized in determining their energy needs or a marketable product as the source of income in supplying waste to the bio-energy plant that could be got within their area. This will enable the communities to have a whiter, healthier environment and potential job creation and admission to improved energy that improves their living standards. The same uses with biomass, wind and hydro energy resources fail to be taxed.

The measurements received from the solar radiation and humidity climate weather data through the instruments utilized are much subject to stability error function as exposed to heat transport within the aura. This heat transfer is of the drift by 10% of the determined values. In summation, there is a relatively 1% humidity loss of the instruments per month. According to [24], many available studies refer to the global solar radiation models. This includes available models in estimating the daily, weekly, monthly, and annual radiation used for solar energy estimation purposes.

## 2. Materials and Methods

Throughout the study, the following materials, methods, and analyses were carried out during the estimations and modeling, namely: - Weather data measured throughout the installed metrology weather stations, the GIS maps obtained through Remote Sensing and Mapping downloads for the Vhembe District and using the Photovoltaic graphical modeling through the Matlab software.

*Basic Solar Irradiance Measurement*

Solar radiation depends on the sunshine that arrives on the earth during the daytime, with its specific latitude location and the atmospheric transmittance (K). Besides the net solar radiation reaching the earth's surface, some are lost and be used for other heating methods, which are turned into additional energy that can be measured using specific instruments [16], [19].

The radiometer is an instrument for measuring irradiance in equal quantities of solar energy at a specified wavelength range measured. The most significant concern was thought in choosing a site placement regarding the determined climatological measurements within the country of interest during the day or in the year. Besides, it was understandable that new models and techniques exist and are being developed in improving the measurement techniques for estimating solar radiation energy with accurate, readable available meteorological parameters. Hence, considering solar radiation on horizontal and tilted surfaces forms part of the estimations [20]. Furthermore, in computing the global radiation, one should take the daily solar radiation absorption (Rs) on the ground, together with the extraterrestrial insolation (Q) and the mean daily solar through the sky transmittance (K) according to equation 1:

$$Rs = Q \times K \quad (1)$$

The constant, K, has a variation of $K_C$ or $K_O$ when there is a clear forecast and $K_i$ on the intermediate days during the year [18], [21]. In summation, in estimating the direct solar radiation (I), one must recognize that it depends on the actual length (r) between the ground and sunlight during the incident measurement. As such, direct solar radiation (I) is known as the dower of the so-called extraterrestrial solar radiation (Io), which arrives at the earth's surface directly from the atmosphere [20], [24].

*Basic Solar Radiation Intensity*

The parameters affecting the solar radiation intensity within the atmospheric region are important in solar energy as other arrays are reflected throughout the air. That is, the spectrum of the radiation emitted by the sun is about the power in the ultra-violet region as the solar radiation beam (i.e., constant ($I_0$)) passes through the atmosphere when the sun is at its mean distance from the earth [21], [22], [25]. This value is

$$I_0 = 1.37 \pm 0.02 \text{kW/m}^2 \quad (2)$$

This constant varies as the light travels through the clouds, absorbed or scattered, reflection and based on the climate latitude and longitude of the location area for the solar energy. This value diverges by 3% as the earth's orbit is elliptical, and the distance from the sun varies all year round. The variations distance between the sun and the world is due to the earth's orbit caused by the actual intensity of solar radiation outside the atmosphere to differentiate from $I_0$ by a few per cents to strike into account these variations by a mean factor, F in Degree Celsius.

$$F = 1 - 0.0335 \sin 360(n_d - 94)/365 \quad (3)$$

Where $n_d$ is a specific day of the year (i.e., $n_d$ = 1 for January and $n_d$ = 365 for December), the argument of the sine function is in degrees. All the values of solar radiation intensity given below, which are in the sun at its average distance from the earth, must be multiplied by F to obtain the actual values on a day. During January, as the weather is clear, the sun is closer to the world, the solar radiation is 3% larger than the average, and in July, when the earth is furthest from the sunshine, the solar radiation is 3% less than the norm.

*Prediction Model and Determination of Solar Energy Radiation at Specific Area and Particular Time*

The site selection directly impacts the potential renewable energy systems (RES) projects in many different ways, including technical, economic, and environmental aspects. However, one of the critical roles in the PV power plants is the inconsistency and variability of solar irradiation, which can be geographically dissimilar from one location to another [23], [28]. To measure the specific amount of solar radiation at a particular area and a specific time, it is essential to define the angle of inclination by cos(δ) of solar arrays to the perpendicular of the earth by considering the area of interest, cos(θ) and expressed by the total amount of watts per meters square ($W/m^2$) and the joules per meter squares ($J/m^2$) [12], [25]. Also, the RE subject field requires three parameters, namely, global horizontal irradiance (GHI), direct normal irradiance (DNI), and diffuse horizontal irradiance (DHI) [13], [24], [29]. Furthermore, many methods have been introduced to measure global solar irradiation in that respect. These methods have been modified in several ways to suit different models. The simplest example to calculate the global solar radiation is shown in equation 4 [3], [25], 30

$$H = H_O\left[A + B\left(\frac{n}{L_d}\right)\right] \quad (4)$$

The H and $H_O$ are the daily solar radiation and the daily extraterrestrial radiation in $MJm^{-2}d^{-1}$; A and B are constant-coefficient; n and $L_d$ are the sunshine hours per day and location day length in Hours (hrs). The constant-coefficient values are subject to the location of the study and its weather conditions throughout the year [25], [28]. Using the captured weather data, several states are shown using the equation to estimate solar and weather conditions.

In measuring the solar radiation, territorial solar irradiation ($E_{ss}$) and global solar irradiation (EET) are considered. Hence, the total solar energy ($E_s$) above the atmospheric level is equal to the absolute atmospheric solar power at sea level multiplied by the length of day (N) per change of temperature (T) throughout the year as determined by equation 5. The latitude (L) and angle of declination (δ) by the sunlight must also be consider parenting the surface of absorption [31].

$$E_s = (Io + 1) + 0.34 \cos\frac{2\pi N}{365} \times L \quad (5)$$

Where the Io is the solar constant = 1,367$W/m^2$ (is the extraterrestrial radiation as the earth orbits around the sun) and N is the number of the day for solar absorption, 0.34 being the constant coefficient of solar irradiance at the atmospheric level and *L* is the length of the day being calculated by equation. The $\cos\frac{2\pi N}{365}$ It is the calculated angle of declination of the sun during the day through per year during the earth's orbit.

The length of the day was calculated by: -

$$L = \frac{2}{15}\cos^{-1}(-\tan L \times \tan\delta) \quad (6)$$

This was determined by the length (*L*) of days per the solar decline angle (δ) as calculated by equation 7.

$$\delta = 23.45 \sin\frac{(284+N)}{365} \quad (7)$$

In normal circumstances for the Vhembe Region weather measurements, the minimum length was 11.2hrs, and the maximum size of the day was 13.9hrs [3], [25]. Therefore, the solar energy ($E_s$) for the minimum and maximum was determined by equations 8 and 9.

$$E_{s(\min)} = (I_0 + 1) + 3{,}808 \cos\frac{2N}{365} \quad (8)$$

$$E_{s(\max)} = (I_0 + 1) + 4{,}726 \cos\frac{2N}{365} \quad (9)$$

As a result, equations 1 to 7 were acknowledged in the patterns, estimations, measurements, and computations of the solar radiation energy and demonstrated by the Matlab graphical responses in Figure 17 to Figure 19 for the radiance measurements.

## 3. Analysis and Discussions

### 3.1. Meteorology Data Acquisition Analysis

Measurements were remotely captured throughout one year, from January to December 2018. The data acquisition (DAQ) system was used to obtain data from the nine Weather Stations (WS) used during the data collection (i.e., Hanglip, Shefeera, Tsianda, Thohoyandou WO, Dzanani Biaba Agric, Mphefu, Joubertstroom Plantation, Vondo - Bos and Tshivhasie Tea Venda). Table 2 gives the locational longitude and latitude coordinates of the installed weather stations used during the data collection for the study.

Table 2. The location of the weather stations installed in the Vhembe District

| Weather Station Name | Longitude (°, E) | Latitude (°, N) |
|---|---|---|
| Hanglip | 101.07 | 41.95 |
| Shefeera | 94.68 | 40.15 |
| Tsianda | 98.48 | 39.77 |
| Thohoyandou WO | 103.08 | 38.63 |
| Dzanani Biaba Agric | 100.13 | 37.33 |
| Mphephu | 30.03 | 22.89 |
| Joubertstroom Plantation | 22.57 | 29.19 |
| Vondo - Bos | 30.33 | 23.93 |
| Tshivhasie Tea Venda | 22.96 | 30.35 |

It was challenging to measure solar radiation in many locations due to the cost of equipment to be used, maintenance, and calibrations to obtain accurate values. Hence, the South African Weather Stations (SAWS) meteorological weather data were used in all the nine weather stations (WS) been installed, in concert with the Agricultural Research Council for the Institute for Soil, Climate and Water (ARC-ISCW) in providing the data. As the results, within reference to the measurements obtained, the data were used to define the solar energy potential for the Vhembe District at specified locations to evaluate its amount for power generation. This data was remotely captured and used to calculate the potential solar energy per location for power generated by photovoltaic system modules. Table 3 shows essential parameters in measuring solar irradiation at different positions. These were applied to evaluate the accessibility of solar irradiation at the designated place.

Table 3: The measurements units used for solar radiation evaluations

| Parameters | Units |
|---|---|
| Global radiation | G (W/m$^2$) |
| Diffuse radiation | $G_d$ (W/m$^2$) |
| Beam radiation | $G_n$ (W/m$^2$) |
| Sunshine hours | σ (hrs) |
| Maximum and minimum temperature | $T_{min}$ and $T_{max}$ (°C) |
| Humidity | H (%) |
| Pressure | P (Pa) |
| Visibility | F (m) |
| Wind speed and directions | V(m/s); N,W,E,S |
| Air mass | ρ(kg/s) |

Besides, the efficiency and error calculations were considered difficult to measure the solar radiation at the geographical location due to other factors, including absorbed or reflected by the atmosphere. Following the data obtained, available renewable energy resources within the Vhembe District were of importance and the peoples' quality of life as purpose in using the solar energy to meet their energy demands.

Figure 14 and Figure 15 show the monthly graphical meteorological analysis of the area for minimum and maximum temperature and the length of the day (sunshine hours) as per the yield throughout the year on the direct solar radiation measurement. These measurements were acquired through the day's duration in the district to get a micro solar system for the community expectation and energy demands.

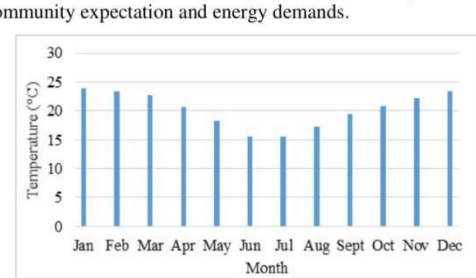


Figure 14: The monthly temperature measurement (Average - 20 °C)

It was noticed that the highest values of the solar insolation are during the summer months (Jan to Apr and Sept to Dec), and the lowest values are during the winter months (May, Jun, Jul, and Aug) as applicable per the day during that time for the season.

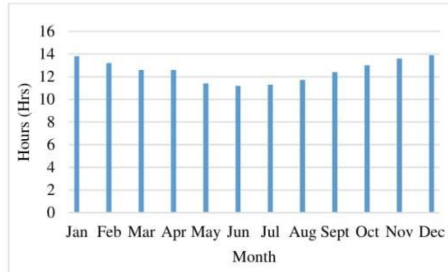


Figure 15: The monthly length of the day measured (Average - 12.5Hrs)

Furthermore, the desirable amount of solar energy was measured during the allowable day time duration (from 06:00 – 19:00) for the whole year per location during the 24hr time interval. The measurements were used to determine the minimum and maximum coefficients variations through the solar radiation calculations using the Matlab software analysis.

### 3.2. Remote Sensing and GIS Mapping Analysis

The Vhembe District is situated at 22.7696° S Latitude, 29.9741° E 25 Longitude of the Limpopo Province. At an altitude of 250m above mean sea level, a study was conducted in estimating the monthly and annual solar radiation, using the climate and geographical parameters. These areas and the outcomes obtained will assist the researchers and public entities interested in working on solar energy developments to have reference and locations' conditions that they can use for solar energy estimation. Figure 9 shows the potential solar available within the district and per municipality used for domestic use during the solar energy estimation. This map provides an overview of available heat energy to be used.

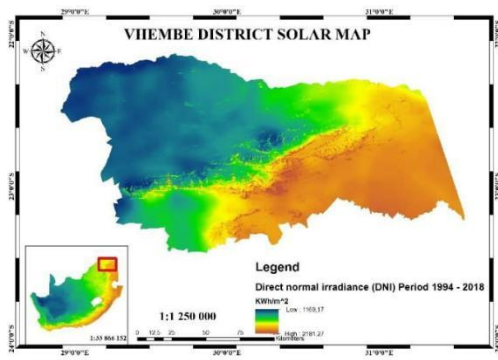


Figure 9: The Solar Map of the Vhembe Strict Area

The analysis shown includes the daily solar radiation assessment from all the locations and using other parameters to see the solar potential available, as shown by Figure 10 to Figure 13. Thither are many solar radiation databases available for most sections of the countries around the globe.

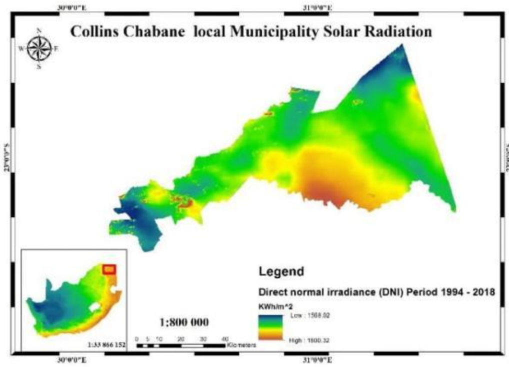


Figure 10: The Areal Solar for the Collins Chabane Municipality

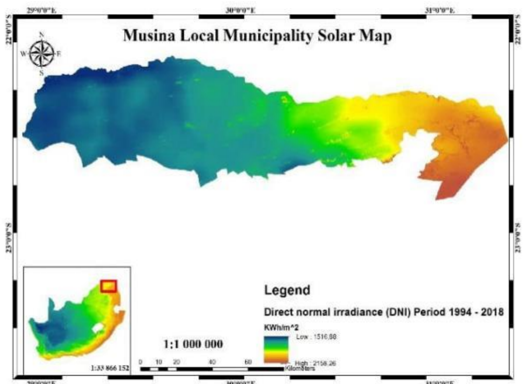


Figure 11: The Musina Municipality Solar Map

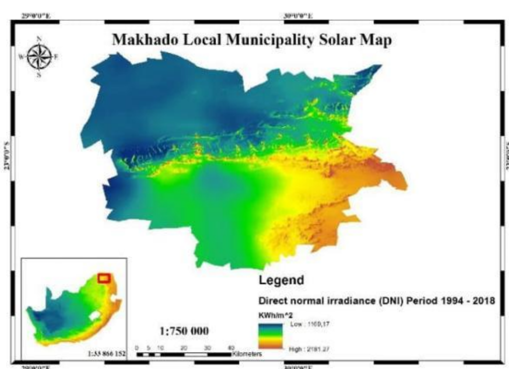


Figure 12: The Thulamela Municipality Solar Map

These were set for the annual weather changes to determine the solar maps of the Vhembe strict and its municipalities (Musina, Collins Chabane, Thulamela, and Makhado Municipality). As a result, the Remote Sensing (RS) for GIS was employed to settle the territorial dominion's solar maps.

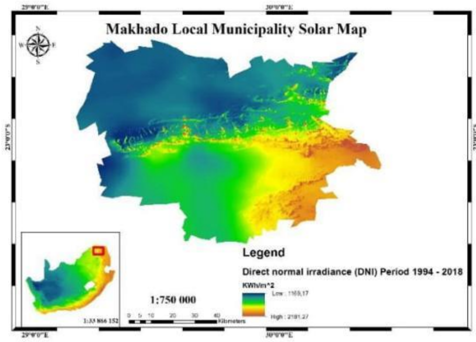


Figure 13: The Makhado Municipality Solar Map

### 3.3. Computational Solar Analysis using Matlab

During the data analysis, the daily solar radiation, the intensity of direct radiation (W/m²) through an average sun hour of the solar insolation, as shown in Figures 17 to 19. It was noted that high radiation is received during the summertime. There are low irradiance and temperatures in wintertime, which is demonstrated by the lowest and highest measurements for power potential and public presentation.

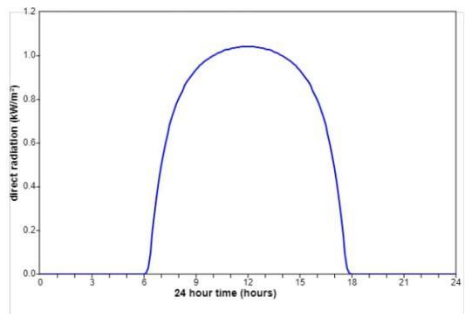


Figure 17: The daily solar radiation for the district

Figure 17 shows the daily solar irradiance curve during the number of hours during sun hours of the day. This is the direct radiation per hour that is generated.

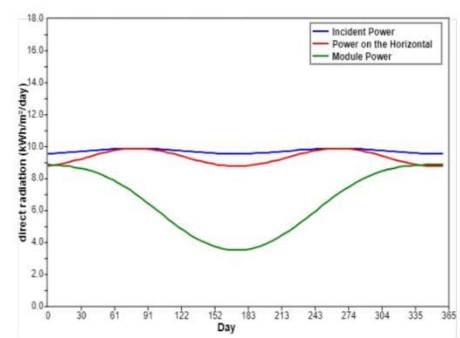


Figure 18. The daily incident power generation per direct intensity

Figure 17 to Figure 19 shows the maximum amount of power directly received without any clouds during the regular sun hours. This amount is set at different to determine how much the specific location's radiation is per period defined. As a result, the power required is generated.

The area is known for its abundant radiation and available solar resources, which significantly influence the design, configuration, and cost of power systems produced. It was observed that the highest values of the solar insolation are during the summer months (Jan to Apr and Sept to Dec), and the lowest values are during the winter months (May, Jun, Jul, and Aug), as demonstrated by Figure 14 to Figure 19. These estimates and weather patterns have been obtained and analyzed through weather stations installed in the Vhembe District and the Matlab software analysis as part of the computations estimations.

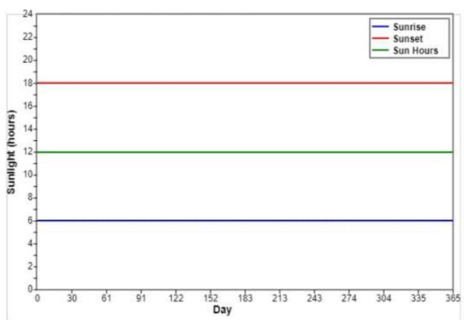


Figure 19. The average sun hours of the solar insolation

Figure 19 shows the mean daily solar availability based on the three curves corresponding to the incoming solar insolation. The daily insolation shown is the number of sun hours rising and sunset. The limited results are helpful for the conception and estimation of the power module needed to take out the solar energy schemes to be set up. This will provide the estimates of the available irradiation generation concept.

The approximation of solar radiation energy is vital in designing the solar energy system or devices. The estimation and size are not easily determined due to the cost and techniques required to practice. As a result, there is a demand for building theoretical methods for estimating solar radiation, such as the empirical relationships using commonly measured climatological data measured at the specific area [17], [18]. Due to its position and extensive territory, the Vhembe District has a complex topology, hill, and mountainous zone area; hence, the nine installed weather stations found different climate data.

## 4. Conclusions

The estimation model uses the most recent data measured throughout (January to December 2018) of the meteorological data obtained in the nine installed weather stations. This analysis demonstrates that the required solar radiation values for the potential use in the field are accepted by the temperatures commonly measured by the installed weather stations around the Vhembe District. The obtained results can be the best exemplar for solar estimation at different geographical and climatic locations.

In estimating PV radiation's optimal and potential role, it is essential to consider the location suitability to maximize the solar energy received and the power generated at the selected position. In this paper, the meteorological estimations, graphics, and formulae were applied to influence the behaviour of the Vhembe District climatic conditions as one of the rural regions of involvement in deploying renewable energy technologies such as solar schemes. Consequently, the analysis demonstrates that the required solar radiation values for the potential use in the field are estimated by the temperatures commonly measured by the installed weather stations around the Vhembe District. Furthermore, intensive research studies within specific locations should be carried out to identify and find out the environmental matters linked with the placement and its natural resources to see potential energy sources available for community use.

It is noted that the active use of solar energy schemes has an environmental impact compared to other authors. These solar energy technologies should be increasingly introduced within the rural areas taking into account the suitability and energy potential of the region.

In summary, solar energy provides many advantages over other alternative energy sources. As presented in the paper, a simple principle of solar heat energy can be utilized in various applications. Nonetheless, it is mentioned that solar energy has its drawbacks or limitations like high initial price, depending on the weather, and challenges in energy storage. As a result, the South African Government is increasingly introducing initiatives with plans in providing subsidized programs to increase an effort in encouraging solar energy use in the rural regions. With the application of the solar assessment, the local community will use these findings to assist in determining the potential locations to deploy and install the solar systems for their local use, agriculture, and community use.

**Disclosing a conflict of interest**

The authors have no conflict of interest to declare.

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# CHAPTER 4: Assessment, Estimation, and Modelling of Wind Energy Potentials

**Article 3**: Assessment, Estimation, and Modelling of Wind Energy Potentials in the Vhembe District, Limpopo Province

There is a need to seamlessly combine the exploration of potential sources with the modeling capability to provide a comprehensive model of both potential and optimisation.

GIS is used to create a map book and accurately locate the right site with available data to help investors and developers locate the best areas and show GIS's potential role in renewable energy.

This study assessed all four municipalities within Vhembe District Municipalities to obtain the overall wind energy potentials map. As a result, a spatial decision support tool was developed in a GIS environment to identify the feasible locations and development to assist decision-makers in facilitating the decision process for selection.

The research results provide renewable energy project investors and planners with scientific information regarding renewable energy potential and suggestions for renewable energy development by quantifying and mapping the wind energy potential, annual energy yield, and the influence on the energy policies for economic potential.

As a result, the wind energy potential was determined by calculating the annual average wind speed for a specified location. The wind speed data obtained from the South African Weather Service (SAWS) metrological data and local government was used to analyse and assess the wind data into seasonal times such as winter, summer, spring, and autumn. The maps were generated through the ARGIC GIS to help identify the most and the least suitable potential wind energy mappings, as demonstrated in the produced article.

# Assessment, Estimation, and Modelling of Wind Energy Potentials in the Vhembe District, Limpopo Province

**Clement Matasane[1*], and Mohamed Tariq Kahn[2]**

[1,2] Department of Electronics and Computer Engineering (DEECE), Cape Peninsula University of Technology (CPUT), Bellville, Republic of South Africa (RSA).

* **Correspondence:** matasanec@cput.ac.za; Tel: +27 (0) 21 460 3383.

**Abstract:** Assessing wind resources is a significant challenge worldwide, and scientists continue to exploit its potential as an energy and usable resource. When deploying wind systems, consider the location and possibility for application. These are household electricity, water use, irrigation, and small-scale projects that benefit the community and their needs. This paper demonstrates the spatial mapping of the wind energy potential and availability in the Vhembe District, considering the weather conditions, environment, and land use suitability. The research methods include the Geographic Information Systems (GIS) and Remote Sensing (RS) techniques in mapping the wind potentials and the metrology data obtained from the installed weather stations. This research found that the potentials for wind energy vary at different locations across the Vhembe District, Limpopo. This paper contributes to the overall research project on remote sensing (RS) and mapping for energy assessment and the potential use of the *Conceptual Framework for Identification of the Rural Energy Deployment Application* tool in supporting the community and decision-makers in implementing wind energy projects.

**Keywords:** Climate data, geographical data, local environmental conditions, wind energy assessment, wind energy potential, wind maps, geographical assessment, wind characteristics, and energy deployment

## 1. Introduction

There are different models and frameworks in rural energy assessment and deployment throughout the region. The conceptual framework presented in Figure 1 identifies the rural energy deployment applications. Renewable energy is an umbrella term for all sources, including solar, wind, hydropower, biomass/ biogas, geothermal, tidal, ocean, and waves [1]. In today's life, wind plays a vital role and importance by being captured and turned into generating electricity.

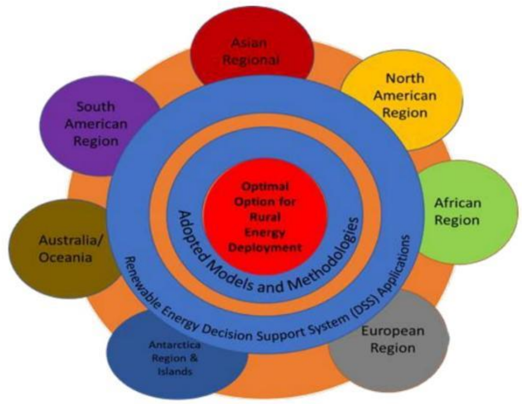



**Figure 1. Conceptual Framework for Identification of the Rural Energy Deployment Applications (Source: Author).**

As a result, the wind is a significant and promising renewable energy source (RES) compared to other RES because of its low adoption, utilization, and production within the globe. The wind system plays a significant role due to its low cost and easy maintenance [2]. Furthermore, in referring to the 2020 IEA report on sustainable development from 2002 to 2030, there are currently only 27% of existing projects in 2019, as shown in Figure 2. It is evident that renewable energy deployment is still a challenge and has delivered more improvement and new developments are being implemented across the country to address the energy mix.

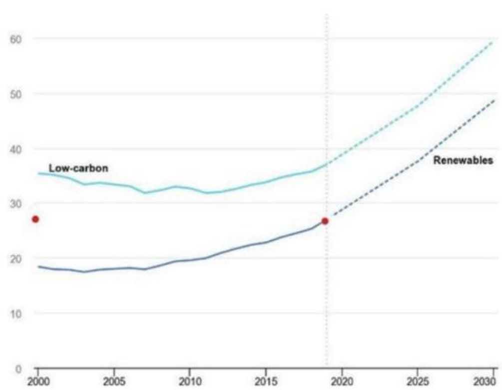



**Figure 2. The 2000 to 2030 Sustainable Development Scenario for South Africa Renewable Energy Development: © IEA, 2020.**

In realizing that the lack of modern energy is worsening the poverty in the rural areas, the Republic of South African government shows commitment to this policy document which intends to give a much-needed thrust to renewable energy, particularly in rural areas. The intervention on renewable energy even though there are no specific or quantifiable renewable energy sources to be provided to the rural people, the policy envisages a range of measures to integrate renewable energies into the mainstream energy economy [3]. Some of the main benefits of the policy will be the provision of renewable energy for rural communities, small schools, and clinics that are far from the national electricity grid.

The provision of modern energy to rural areas will increase lighting and power their equipment used for commercial and production. Most importantly, notably free women and children from collecting firewood [4]. Confirming the durability and reliability of renewable energy systems, the [5] revealed that hundreds of thousands of renewable systems had been installed throughout rural areas of the developing world. All these measures are geared toward the Sustainable Livelihoods Approach (SLA), a way of thinking about the objectives, scope, and priorities for development to speed up progress in poverty elimination [6]. This calls for immediate intervention to develop efficient and safe technologies to relieve such people like women from the burden of hard labour for cooking, collecting water, and domestic use. In addition, the short and medium-term goals should be developed to meet these challenges towards the electricity infrastructure in the application of imaginative grid concepts and renewable technologies [7].

The adoption of renewable energy technologies and promotion of green energy is being recognized internationally as a way towards independence from fuel oils and being provided by the natural environment as one of the most widely exploited and rapidly evolved [8].

Throughout the world, there are two main driving forces of the countries being behind the renewable energy development: such as the current challenges on climate and global warming and the requirements by governments to secure and develop their renewable power plants [9]. Ramachandra [10] reported that renewable energy is defined as energy that comes from natural resources that are constantly replaced in nature on a human timescale, such as sunlight, wind, rain, tides, waves, and geothermal heat and thus the reasons being commonly accepted as the vital energy sources for future life in the world.

All these technologies and their factors, as well as their applications, are accompanied by uncertainties and complexities, which are difficult to be controlled by decision-makers without significant expertise. It is, therefore, appropriate to develop an effective distributed energy system planning tool, which decision-makers can easily use under various spatial measures [11]. As a result, proper assessment of their potential is essential in planning and promoting renewable energy technology [12, 29].

The pursuit of reducing environmental impacts of conventional energy resources and, more importantly, conforming to the growing energy requirement of the global population has motivated considerable research attention in a broad scope of environmental and technology application of renewable forms of vigor. Wind energy by nature is clean, abundant, affordable, inexhaustible, and environmentally preferable. Due to its many advantages, wind energy is one of the fastest-growing renewable energy sources in both developed and producing nations. For instance, wind energy is widely created to make electricity in states like Denmark, Spain, Germany, and the USA [13].

The proper exercise of these wind energy potentials will ensure the promotion of socio-economic development and the quality of liveliness of the people. Extending the utilization of renewable resources such as wind will cut carbon dioxide discharges, which lead to global warming and lower long-term overdependence on fossil fuels. Further, wind energy, like other power technologies based on renewable energy resources, is fast evolving globally and widely available, thereby ensuring the security of supply. Figure 3 shows the primary wind energy power supplies that have been developed within the Republic of South Africa. These supplies are primarily in the outshore of the country around the coastal access and where the most wind could be found. These are found in the Western Cape, the Eastern Cape, and the Northern Cape.

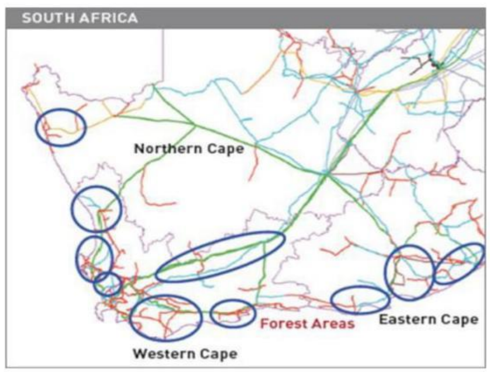



**Figure 3. The major wind energy projects developed within South Africa: - © GTZ, 2009**

Before constructing any wind farm, detailed verification of the specific on-site wind conditions is necessary. This paper thus seeks to present an overview of the district wind energy potential by assessing, estimating, and modeling of the wind power potential in the Vhembe District area, as shown by the obtained geographical information system (GIS) map in Figure 4. These are being evaluated as per its selected sites to compare the wind energy generated, estimated, and potential use for power generation at a considerable amount.

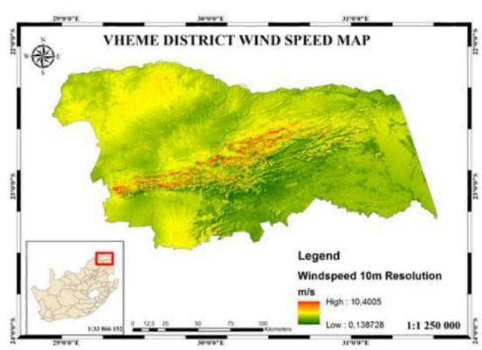


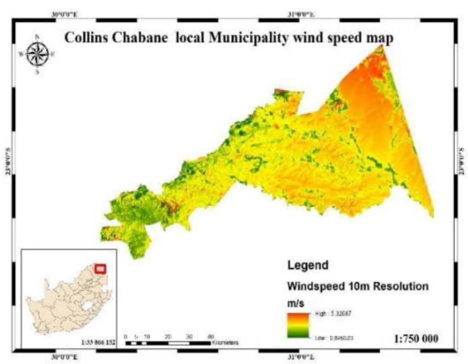
**Figure 4. The wind speed map of the Vhembe District.**

## 2. Materials and Methods

*Study Side and Geographical Data for Wind Energy*

The assessment and estimations for possible deployment of the wind energy focus on the 10-meter height allowance for typical wind farm systems, data assessment, capacity, annual energy, and energy outputs. The weather conditions and data sources were harvested from January to December 2018 (including daily, monthly, seasonal, and yearly variations during the measurements and recordings) to obtain measurements of wind average to be used in determining wind potentials.

The district has four municipalities with limited electricity connectivity and faces energy challenges, especially on their socio-economical balance. The area is situated at 22.7696° S Latitude, 29.9741° E 25 Longitude of the Limpopo Province, and 250m above mean sea level. Evaluation of the wind energy systems is being considered to assist or support the rural and disadvantaged communities for their micro/small wind energy supplies. This wind energy could be cost-effective, especially on the agricultural, small farming, poultry, and irrigation for the rural communities. As such, Figure 5 to 8 shows the four local municipalities' wind speed potentials obtained from the GIS map. Furthermore, it is recorded that the weather and climate data were obtained from the South African Weather Services and Water Research Commission (WRC) Department. The municipalities' geological study sites are shown in Figures 4 to 7.



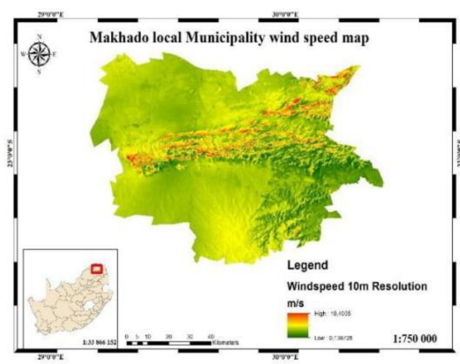
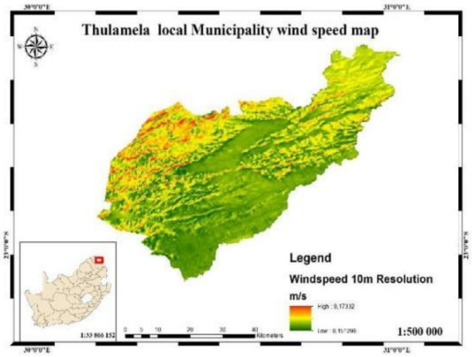




**Figure 5. The Collins Chabane wind speed map. Figure 6 . The Makhado wind speed map.**



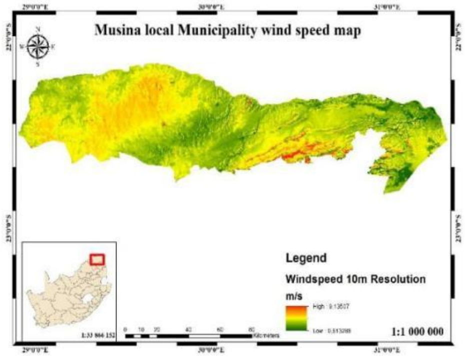




**Figure 7. The Musina wind speed map.** **Figure 8. The Thulamela wind speed map.**

In addition to the above GIS maps, the wind speed was obtained on the installed stations at the Thohoyandou WO (coordinates: -23.0790 30.3830) and the Tshivhasie Tea Venda (coordinates: -22.9700 30.3500) at an average wind direction from the Degree North. These wind speed measurements were extracted during 08h00, 14h00, and 20h00 periodically, as shown in Table 1.

**Table 1. The Installed Wind Speed locations and land.**

| Wind Station Name | Longitude (°, E) | Latitude (°, N) | Elevation (m) | Land Cover |
|---|---|---|---|---|
| Thohoyandou WO | 23.0790 | 30.3830 | 614 | Urban |
| Tshivhasie Tea Venda | 22.9700 | 30.3500 | 967 | Sparse forests |

Currently, wind energy is one of the fastest growing renewable energy technologies being developed globally and mainly onshore. In addition, the wind is among the cheapest renewable sources per unit of electricity produced. Analysis indicates that a land-based 2.5MW wind turbines network could supply over 40 times current worldwide electricity consumption.

The wind energy generation market is continuously growing worldwide. In referring to 2009, 82 countries used the wind to generate energy, and 49 countries increased their installed capacity. The Middle East and Africa also recorded 230MW of newly installed capacity, with an estimate of a 90% growth rate in Morocco and 70% growth in Tunisia. These developments of wind energy are small compared with wind energy produced in regions, like North America, Europe, and Asia. The presence of wind energy in remote locations of the world highlights the continued rapid growth in global demand for emissions-free wind power, which can be installed virtually everywhere around the globe. Wind energy had over 238GW of installed capacity at the end of 2011 and is expected to play a crucial role in mitigating future greenhouse gas emissions. The Global Wind Energy Council forecasted that the global wind market would grow by over 155% to reach 240GW of total installed capacity by the end of 2012. According to recent projections, wind energy is expected to contribute some 12% of global electricity by 2050, with 57% of this energy produced by non-OECD economies. However, USD3.2 trillion will have to be invested over the next 40 years to realize this improvement. Currently, Europe is the leading market for global wind power and will probably remain so for the next decade. It is followed by the United States and then China as world-leading wind power producers. China will likely overtake the United States and OECD Pacific countries as a major producer of wind energy by 2050, with a projected figure of 1660 TWh. The rest of the world, including Africa and the Middle East, will provide nearly one-fifth of wind electricity in 2050 [3,6,14].

The history of wind energy in South Africa has been published in many articles and news. Evidence has been produced by many researchers, industries, and experts regarding wind energy power, map/s, costs, advantages and disadvantages, and challenges.

From the environmental perspective, energy is connected with the natural resources that are continuously available, including solar, wind, hydropower, and biogas/ biomass that are locally available. Thus, developing countries are currently faced with challenges to increase their energy production to accelerate their development and raise their community living standards while considering the CO2 emissions. The use and adoption of renewable energies must be a priority taken by the governments to improve energy efficiency and reduce pollution [15]. The countries should focus on the end-user-oriented approach to achieve sustainable human settlements' development goals by completing the objectives. The actions to be taken by the governments should incorporate renewable energy sources into the national energy matrix [16].

The current scientific reports confirm that renewable energy resources deployed in developing countries can reduce poverty and human well-being by creating employment and business opportunities [17]. These energy resources can be used for domestic and economic requirements such as cooking, heating, lighting, powering schools, clinics, commercial, and farming. Mainly reducing the time that children spend out of school collecting wood, waste, and fuel from traditional use at home and improving their quality of health [18]. By Pegels [19], the available data show that approximately 4% of the country's estimated electricity demand, very little has been channeled to the rural and remote areas of the country for sustainable development in energy mitigation and needs.

Lutgens and Tarbuck [20] defined wind as the pressure gradient that provides the impetus for air movement in selecting wind energy. It is also defined as the movement of atmospheric motion at a broad range of scales affected by different temperatures from low and high altitudes [21]. These altitudes cause the difference in air masses' movements under other thermal conditions.

This paper contributes to the wind energy estimation as it is based on the location where the development is being carried out and to determine the optimal use of wind energy at a specific site. This helps determine the coefficients and magnitude correlating to the results of qualitative studies with statistical analysis of available records. Data gathered at the installed stations have been analyzed to support the evaluation and planning of future wind energy projects in this coastal region [22,30].

## 3. Results

*Wind Energy Mapping and Its Variations*

In determining the wind speed potential in the Vhembe District, various measurements were conducted and recorded to estimate its energy potential. During the analysis of data captured from the installed weather stations, it was indicated that the wind directions were from true North to clockwise with available ranges where applicable. Table 2 below shows the direction ranges of wind in the Vhembe district. In order to determine the average wind speed, the recordings were done three times during the day, especially in the morning, afternoon, and at night to obtain variations due to the humidity. These ranges were recorded during 8:00 am, 14:00hours and 20:00hours. As a result, several wind analyses were obtained as indicated by the period measured. The wind measured during the early morning differs from one during the day and in the evening, as illustrated by the graphs.

**Table 2. The Wind Speed direction and coordinates.**

| | | | |
|---|---|---|---|
| N | dir>=348.75 OR dir < 11.25 | NE | 33.75 to 56.24 |
| E | 78.75 to 101.24 | SE | 123.75 to 146.24 |
| S | 168.75 to 191.24 | SW | 213.75 to 236.24 |
| W | 258.75 to 281.24 | NW | 303.75 to 326.24 |

The daily wind measurement and analysis were obtained during the morning hours, midday, and evening monthly throughout the year. Hence the graphs show three different sizes per location per time.

In considering the land use for the wind energy system, there are projects in which a land-use change is not required or necessary as they are on a small scale for individual applications to meet the projects' needs and typically are boundary configured in order to facilitate the project requirements. In most cases, where approvals are required in terms of the laws, land-use for such as the heritage and environment would be affected by the projects. These are implemented through regulatory authorities and the land acquisition process. In typical villages, all officers lie with Enduna or Chief of the community and the local government municipality.

Considering large-scale wind projects require spatial planning for the decision-makers to utilize land properly and minimize risks and hazards to natural resources, infrastructure, and social activities to the people [23]. Furthermore, this process of allocating and developing the landscape for multiple functions is the responsibility of all the planning agencies, government, and local communities. Hence the importance of the environmental impact and assessment at different levels requires all the stakeholders for economic and livelihoods sustainability of the land use and resources [24,25].

However, worldwide and currently in the Republic of South Africa (RSA), the wind energy potential and assessment still pose a significant challenge to all researchers, government, industry, and communities in exploiting its possibilities and cannot be ignored. Hence, it is critical to have wind energy assessment and modeling when developing wind farms at specified locations [26].

As a result, the metrological, spatial information and analysis become more critical in determining its temporal data, landscape, and coverage to obtain its evaluation for potential use. Thus, it becomes the study's primary aim in the Vhembe district in assessing its wind potential. This study was carried out in a 10metre height for all the assessment, mappings, and modeling been carried out at different locations with the installed wind speed stations for data collection, as an addition to the major project being carried out in determining the power potential through spatial feasibility and the measured wind data at the installed weather stations.

*Wind Energy Estimation and Its Potential*

The wind energy potential obtained with the data produced has been taken from the North degree clockwise from 08:00 am; 14:00, and 20:00 to determine the wind speed within the area. The climate data and diagrams of the sites are taken from the collected data in the study sites during the two years from January to December 2018. The basic formula calculates the energy potential as Equation 1 shows. That is the work done multiplied by the time spent.

$$E_w = P_w \text{ x } T_w \quad (1)$$

The $E_w$, $P_w$, and $T_w$ are the wind energy measured in watts (W), wind power density obtained, and total time (in hours) spent. When the average wind energy is measured throughout the year per the specified area (A) at 1metre perpendicular (or proportional) to the wind speed (U), the annual wind power estimation is obtained by equation 2.

$$P_w(u) = \frac{1}{2}\rho A U^3 \quad (2)$$

The specified area is determined at 1m2 total area (A) of wind power per specified area. As a result, the average wind power density (Pw) measured per selected area through the natural air density (ρ), assumed at 1,225 kilograms per cubic meter (1,225kg/m3). This is a constant used for average air density. Hence, the final wind power density will be determined by equation 3.

$$P_w(u) = \frac{1}{2}\rho U^3 \quad (3)$$

In applying the most straightforward method on wind power density and its potential, [27,28] mentioned that the Weibull Methodology is a suitable formula to be applied. This formula determines the average wind power density obtained at a specified area proportional to the wind speed.

In this study, as chosen for the Vhembe District, the wind speed and direction data were obtained from the South African Weather Services (SAW) and the installed Agriculture Research Council (ARC) weather station from January to December 2018, and it is illustrated in Table 3 for the wind average measurement.

An algorithmic wind estimation on hills and ridges needs to vary from theoretical analysis and logarithmic tests to determine the wind profile. Hence, measuring wind speed at height is essential for suitable wind models and estimation. As a result, the following characteristics are considered: -

1. Height above the ground (in meters)

2. Wind speed (in m/s) Height above the ground (in meters)

3. Wind speed (in m/s) Roughness length of the surface zone (z0)

**Table 3. Monthly average wind speed at 10m height.**

| Month | | Average Wind Speed at 10m Height (m/s) |
|---|---|---|
| January | | 3 |
| February | | 3 |
| March | | 2,8 |
| April | | 2,6 |
| May | | 2,4 |
| June | | 2,6 |
| July | | 2,8 |
| August | | 3 |
| September | | 3 |
| October | | 3 |
| November | | 2,9 |
| December | | 2,9 |

Using the wind profile Algorithmic at rough estimation, the vertical wind profile is obtained in Figure 9. The obtained wind speed profile comes from the established 10m height and the average wind severity speed of 2,8m/s through the year to get the district's average wind power density.

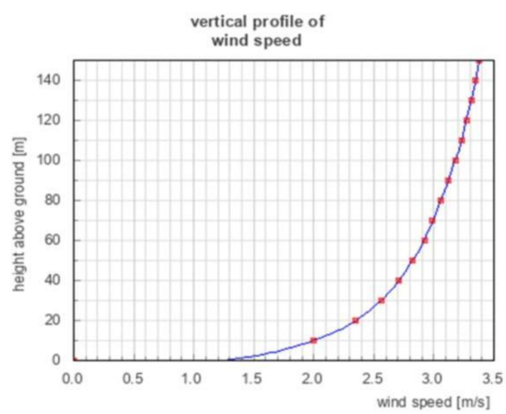



**Figure 9. The wind profile speed under 10m in height above the ground.**

These parameters are used in Table 4 to determine a specific location with specific land cover types and zones.

**Table 4. The wind profile characterization for wind turbines.**

| Roughness Class | Roughness Length $z_0$ | Land cover types |
|---|---|---|
| 0 | 0.0002 m | Water surfaces: seas and Lakes |
| 0.5 | 0.0024 m | Open terrain with smooth surface, e.g., concrete, airport runways, mown grass, etc. |
| 1 | 0.03 m | Open agricultural land without fences and hedges; maybe some far apart buildings and very gentle hills |
| 1.5 | 0.055 m | Agricultural land with a few buildings and 8 m high hedges separated by more than 1 km |
| 2 | 0.1 m | Agricultural land with a few buildings and 8 m high hedges separated by approx. 500 m |
| 2.5 | 0.2 m | Agricultural land with many trees, bushes, and plants, or 8 m high hedges separated by approx. 250 m |
| 3 | 0.4 m | Towns, villages, agricultural land with many or high hedges, forests, and very rough and uneven terrain |
| 3.5 | 0.6 m | Large towns with high buildings |
| 4 | 1.6 m | Large cities with high buildings and skyscrapers |

For further investigation, it was important to determine the area's air density (ρ) to obtain the wind power profile using the on-site measurements. Formula 4 shows this air density: -

$$\rho = a \times e^{-b.z} \quad (4)$$

The exact air density (ρ) calculation is obtained by measuring the air pressure (a) of the specified location, temperature (b), and humidity (z) from the meteorological stations installed at the sites. The material analysis, wind energy mapping, and analysis were conducted using the installed weather stations, namely, the Thohoyandou WO Station and the Tshivhasie Tea Venda Station.

*Wind Energy Potential*

At a wind speed (v), reference to Figure 9, the available energy per unit area perpendicular to the wind stream over a given period of time (t) is expressed by the kinetic energy flux as [12]:

$$E_a = 0.5 \times \rho \times v^3 \times t \quad (5)$$

Where ρ, is the air density (kg/m3), and $E_a$, is the total theoretical energy available for working on the wind turbine as a fraction of the total energy.

The maximum extractable energy from a system working at its optimum efficiency is limited by a coefficient of performance called the Betz limit (16/27 = 0.593). This capacity factor makes the extractable energy approximately 59.3 % of the theoretical energy and is given by [22]:

$$E_m = 0.2965 \times v^3 \times t \quad (6)$$

**4. Discussion**

The determination of wind potential and energy yield at the selected site is carried out by analyzing the wind data, statistical methods, and modeling. Therefore, it is of fundamental importance to determine dependable statements about the wind energy potential and energy yield at every site where wind turbines would be installed [27].

As such, in the area, an annual recording of the wind data was done throughout the year (from January to December 2018) and with the wind setup and development, at 10m height being considered as the average and standard measurement for the wind estimation and power. The Vhembe District is located at 22.7696° S, 29.9741° E of the Limpopo Province. The data from selected stations were analyzed using the two-parameter Weibull probability distribution function. With an annual mean wind speed of 3.8 m/s, annual energy of 158kWh/m2 could be extracted. The wind data obtained has been used for wind estimations, assessment, calculations, and modeling; as Matasane [29] mentioned, the study was conducted through nine installed Weather Stations (WS).

The annual recording of the wind data was done throughout the year (from January to December 2018) with properties in Table 5. The wind setup and development were conducted at 10m height being considered at normal and standard height during the wind estimation and power. The Vhembe District is located at 22.7696° S, 29.9741° E of the Limpopo Province.

**Table 5. Parameters used for wind measurement.**

| **Property** | **Value** |
|---|---|
| Mean speed | 4.115395(m/s) |
| Weibull parameter A | 4.6(m/s) |
| Weibull parameter k | 1.64 |
| Air density | 1.227(kg/m$^3$) |
| Median speed | 3.678749(m/s) |
| Max. freq. | 0.1671578(%) |
| Speed of max. freq. (Modal speed) | 2.591627(m/s) |
| Speed of max. power density | 7.479808(m/s) |
| Variance | 6.629131 |
| Max. power density | 13.5761(W/m$^2$) |
| Total power density | 102.625(W/m$^2$) |

The WAsP, was used to get a statistical summary for the mean wind speed Weibull distribution and the power density for the location.

As a result, the wind energy in the area may be used for pumping water or other mechanical applications and generating electricity. In this assessment, it has been shown that the wind turbines mounted on a tower at 10 m above ground would capture the most wind energy in the region.

In this research, it has been revealed that the highest or most monthly mean wind speed during the year was assessed and determined by its frequency. To ensure that the efficiency and wind conditions are maintained, it would be possible to consider the portable small farmers' applications in the area. As a result, it would be an innovative new way to use the wind power generator with low wind speed turbines at significant altitudes and heights.

## 5. Conclusions

In this paper, the wind energy potential has been presented. The wind energy potential in the Vhembe District area concluded with the following assessments: - It was found that most wind energy systems in the district were used for water pumping in rural areas for small farming and domestic use. Locating the right site can be done quickly and accurately with publicly available data and GIS and Remote Sensing technology as obtained in the study. This would help communities and decision-makers, as well as the investors and developers in locating the best location for wind energy resources in the district. The presented estimation and modeling of wind energy is a valuable tool in wind energy assessment and power estimation for domestic and small farmers for the benefit of economic energy applications.

The wind energy in the area may be used for pumping water or other mechanical applications in addition to generating electricity. In this assessment, it has been shown that the wind turbines are mounted on a tower at 10 m above ground would capture the most wind energy in the region. As such, it has been revealed that the highest or most monthly mean wind speed during the year was assessed and determined by its frequency. To ensure that the efficiency and wind conditions are maintained, it would be possible to consider the portable small farmers’ applications in the area. As a result, it would be an innovative new way to use the wind power generator with low wind speed turbines at significant altitudes and heights. In this research, the monthly and yearly wind has been assessed. In addition, the district has many farming projects which have a high demand for water irrigation and as seasonal, it has been found that the windy season coincides with the seasons and is suitable for the wind-powered water pumping applications as a viable option.

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# CHAPTER 5: Assessment of Bioenergy Potentials for Energy Deployment

**Article 4**: Methodology for Bioenergy Potential and Assessment for Energy Deployment in Rural Vhembe District Areas

This chapter provides the model energy scenarios and develops recommendations for the improved planning of future projects on biomass energy potentials in the study region and to find the optimal locations for biomass power plants.

The biomass or bioenergy potentials were assessed through the compilation and computation of bio-resource supply of all the available waste, agricultural residue, fruits and crops, forest, horticulture residue, plantation and livestock waste, and municipal wastes. The data obtained in the district for bioenergy resources was assessed throughout in determining the availability of resources presented by the environmental factors associated with the biomass or bioenergy potential in the location.

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# Methodology for Bioenergy Potential and Assessment for Energy Deployment in Rural Vhembe District Areas

Clement M. Matasane, Mohamed T. Kahn



***Abstract*—**Biomass resources such as animal waste, agricultural and acro-industrial residues, forestry and woodland waste, and industrial and municipal solid wastes provide alternative means to utilize its untapped potential for biomass/biofuel renewable energy systems. In addition, crop residues (i.e., grain, starch, and energy crops) are commonly available in the district and play an essential role in community farming activities. The remote sensing technology (mappings) and geographic information systems tool will be used to determine the biomass potential in the Vhembe District Municipality. The detailed assessment, estimation, and modeling in quantifying their distribution, abundance, and quality yield an effective and efficient use of their potential. This paper aims to examine the potential and prospects of deploying bioenergy systems in small or micro-systems in the district for community use and applications. This deployment of the biofuels/biomass systems will help communities for sustainable energy supply from their traditional energy use into innovative and suitable methods that improve their livelihood. The study demonstrates the potential applications of Geographical Information Systems (GIS) in spatial mapping analysis, evaluation, modeling, and decision support for easy access to renewable energy systems.

***Keywords*—**Agricultural crops, waste materials, biomass potentials, bioenergy potentials, GIS mappings, environmental data, renewable energy deployment, sustainable energy supply.

## I. Introduction

IN the Limpopo Province, the fuel wood and crop residues are dominants use of the rural communities for heating and cooking. The area is predominant of agricultural activities, hence interested in exploring the bioenergy potential in the area. Most research has been exploited on the application of Geographical Information Systems (GIS) through application in health, agriculture, urban and town planning, telecommunication, climate change, disaster management, wetland planning, environment, and energy use [1]-[4], [6]-[9], [26], [27]. Nevertheless, for the most part, these assessments have been limited in their scope. In many cases the focus has simply been on a single possible source, such as solar [1], [2], wind [3], [4], and biomass [5]-[7]. Although there are a few instances where an exploration of the potential for multiple resources, and the development of a map for each source independently of the other source/s, has been undertaken, a GIS for bioenergy in spatial mapping and evaluation is of interest as part of the renewable energy systems [8]-[11]. For these reasons, a web-based spatial decision support system (SDSS) is a valuable solution in the exploration of energy resources as it has multiple benefits or capabilities such as spatial analysis, modeling, decision support, a friendly user interface, and easy access. However, there have been minimal applications. It is still a relatively new research field integrating GIS, the Internet, databases, technical reports, maps, and modeling to create a virtual instrument for the region's decision support system on renewable energy potentials [12].

Biomass is also the primary energy source for most of southern Africa. However, the justification for its growth differs from Western Europe, where the emphasis focuses on reducing greenhouse gas emissions [13], [14]. The true potential of bioenergy in Africa is social development and economic sustainability. Therefore, Africa's vast resources are essential in developing a socially acceptable, inclusive, and innovative bioenergy sector with balanced financials for sustainable food production and quality of life [15].

Additionally, since energy is not only essential for the advancement of civilizations, but also provides vital services and means to improve the quality of life of individuals and communities, there is therefore a growing need to consider the energy used by households from wood fuel. In terms of the latter, firewood remains the cheapest option [16], [17]. Furthermore, in developing bioenergy systems to complement energy sustainability, there is a need to assess, estimate, and model biomass energy resources in mitigating energy supplies as bioenergy comes from bioresources, biofuels, and bio-residues [18]. These resources include solid biofuels, liquid biofuels, biogases, industrial waste, and municipal waste [19]. Hence, biomass is essential to this study for assessing, estimating, and modeling the Vhembe District to determine its potential for energy deployment using spatial planning maps, environment, and land suitability for the area.

Biomass provides alternative energy supplies to rural communities from the fuel wood and forestry residues [20]. Biomass, a type of renewable energy source, is an alternative to conventional energy sources. These are organic materials that are used as energy for direct heating and combustion, or indirectly as biofuels [6]. In addition, as part of the waste, municipal, manufacturing, food and acro-processing wastes must also be considered in generating alternative energy supply to the communities. As part of the South African energy

C. M. Matasane is with the Cape Peninsula University of Technology (CPUT), Faculty of Engineering and Built Environment (FEBE), South Africa (corresponding author, phone: +27 (0)21 460 3383; e-mail: matasanec@cput.ac.za).

M.T.E. Kahn is with the Energy Institute under FEBE, CPUT, South Africa (e-mail: KhanT@cput.ac.za).

scenario, it is evident from the energy outlook that many people still use electricity, gas, biogas, and biofuels, as shown in Fig. 1.

Biomass power generation is a crucial component of the energy mix in a developing nation like South Africa. Rural communities, especially in the Vhembe District, will be lifted out of poverty and move towards a wealthy and equal future using biomass as an energy system. Access to affordable, reliable energy is essential for sustainable growth on both economic and environmental levels, as the most prevalent crops in the district in terms of biomass are mangos, oranges, apples, litchis, bananas, and sugar cane, which are produced in larger quantities as an agricultural area. There are many different estimates of the total biomass capacity with the leading agricultural crop in the area that can be processed to provide electricity from the leftovers and waste on farms.

Biogas digests can turn waste, such as kitchen scraps and cow dung, into methane gas used for cooking and heating. Biomass can be supplied by dedicated crops of arboreous and herbaceous species, such as annual crops (corn, soy, sunflower, and sorghum), as further illustrated in Fig. 2.

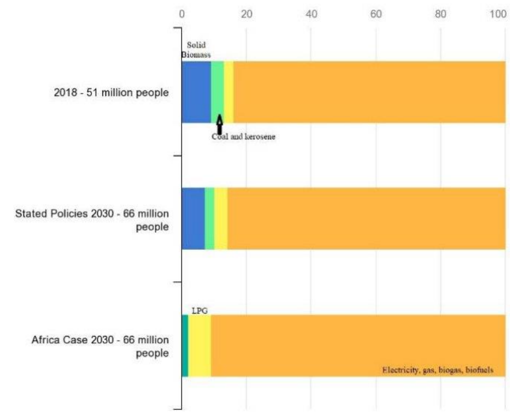


Fig. 1 Impact of South Africans using fuels and technologies for cooking [24]

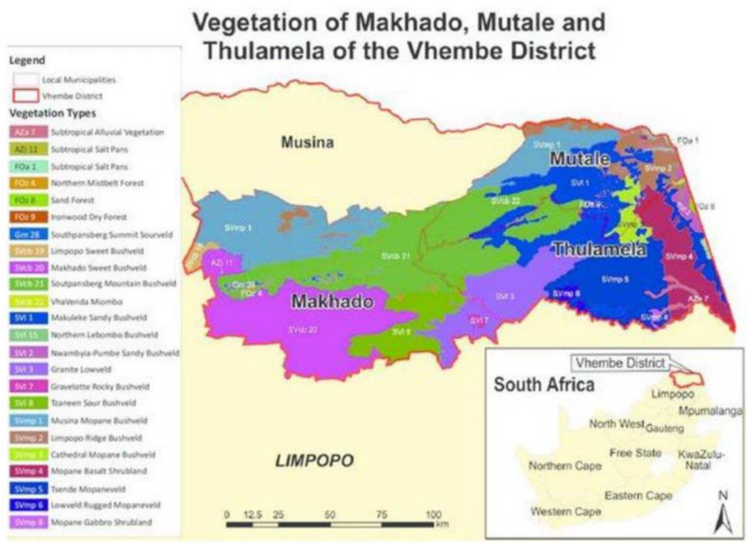


Fig. 2 Vegetation map of the Vhembe District [25]

Several models for biomass and biofuels were developed to support the decisions over which species to grow; the local climate, morphology, soil characteristics, water, and nutrient needs commonly determine the species suitable for a specific area [21].

## II. Study Area

The study domain and characteristics form part of the Limpopo province by the edge of the borders of Botswana, Zimbabwe, and Mozambique through to the Kruger National Park. It shares borders with the Capricorn and Mopani District Municipalities in the south and east, respectively. The Vhembe District Municipality area is one of the five districts of the Limpopo province of South Africa. It is in the country's northernmost district and shares its northern border with the Beitbridge District in Matabeleland South, Zimbabwe. The municipality is in the north of Limpopo province, and its district capital is Thohoyandou. For administrative purposes, the district, as shown in Fig. 3, has been divided into four local municipalities, namely: Makhado, Thulamela, Musina, and

Mutale, with a population of approximately 1,3 million people according to the South African local government [22].

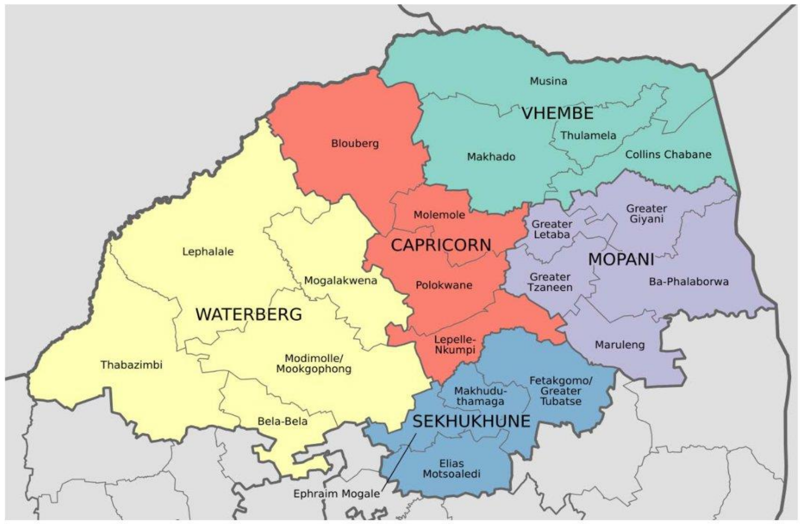


Fig. 3 Vhembe District local municipalities – Makhado, Thulamela, Musina, and Mutale [25]

The annual population growth is increasing; however, new census statistics will determine the percentage. The district is the second lowest on access to infrastructure amongst districts in the province, with a high unemployment rate of 53%. The poverty rate is 32%, making it one of the lowest socio-economic areas in Limpopo Province [21], [22]. The land is very fertile and suitable for agriculture. A large part of the land falls under the tribal authorities. This makes it difficult for development, as the land tenure system could be more favorable towards commercial development. The population comprises 54,4% women and 45,5% men, with 51,3% under 20. The district settlement pattern is mainly rural, with approximately 774 dispersed villages and 287,190 households [22], [25].

The district has 15 primary commodities produced by the smallholder farmers to improve their livelihoods and creation of employment. These include tomato, mango, litchi, citrus, avocado, garlic, banana, macadamia, vegetable gardens, poultry, fish, guava, livestock (cattle, sheep, and goats), pigs, and backyard vegetable products [22]. With such commodities, the idea of waste to bio-energy plants could enable the communities to use their waste materials and turn them into energy. In addition, it can benefit them in meeting their energy needs or a marketable product as the source of income in supplying waste to the bio-energy plant within their area. Providing the waste will give the communities a cleaner, healthier environment; foster job creation; and facilitate access to improved energy which will uplift their living standards.

The municipality is mainly rural, and the citizens depend on agriculture as the main economic activity to sustain and improve their livelihood [22]. Moreover, the municipality is composed of many farmers whose lives could be improved using renewable resources such as livestock waste from chickens, pigs, and cows for economic development, and an increase in employment in the municipality. In addition, with the availability of land, potential crops such as soya beans and sweet sorghum could be commercialized with a view to biodiesel power production [22]. Furthermore, biomass will be converted into biofuels as a form of alternative energy mix. To produce energy, it makes use of organic materials such as those made from wood shavings, sawdust, and firewood, fruit stones like avocado, olive, and nutshells, wastewater, manure, paper waste, and pellets for direct heat and burning [23].

## III. Mathematical Proposal

The biomass or bioenergy potentials are assessed through the compilation and computation of bio-resource supply of all the available waste, agricultural residue, fruits and crops, forest, horticulture residue, plantation and livestock dung, and municipal wastes. The data to be used for this bioenergy resource will be assessed and estimated by applying the following methods:

### *A. Potential of the Crop Residue*

The amount of crop residue in the district is determined by the products available as weighted through the scaled-balanced method. The amount collected is determined by tons of residues which yield the spatial distributions based on the farmland areas.

### *B. Mapping of the Crop Residue Distributions*

Understanding the spatial distributions of the biomass residues throughout the district farmland is based on the availability of field maps and characteristics of the estimated potentials. These forestry residues, including farmed crops such as wheat, sorghum, maize, sunflower, and other wastes, add energy to other forms of waste from grass, trees, and others for biodiesel, bioethanol, and thermal production by using technology to transform them into energy.

### *C. Mapping of the Biogas from Animal Residue*

The animal residues are a vital component of the study which provides a primary indicator of the number of available animals as part of another method for assessing the domestic biogas potential in the district.

### *D. Mapping of the Forestry Residue*

The district has many trees, which offer a viable habitat for evaluating biomass potential and supporting the need to produce electricity. This energy source's tribunal and territorial topology controls it through the timber and plantations available within the district as forest residues.

### *E. Spatial Mapping Waste Residue*

Ordinary solid wastes in municipal garbage include grass, leaves, food scraps, and waste from bioproduction. These wastes produce steam for power production and energy as a form of heating. Landfills and biomass materials such as manure, refuse, garden, and industrial waste combustion are converted into gas to produce energy.

## IV. Case Study and Discussions

Much interest has been in estimating biomass, which will continue to increase due to global warming and its consequences. As discussed, various biomass estimation methods have advantages and disadvantages. In some cases, it is about the accuracy of a particular method. In other cases, it is the cost associated with carrying out a particular method, time, and the labor-intensive nature of the method used. The challenge still lies in available infrastructure, human resources, and funding in developing countries to carry out such development in building biomass projects.

As a result, most African nations use biomass as a valuable energy source for thermal purposes in addition to cooking and electricity production. It is crucial to have an alternative energy source because a significant portion of the continent lacks direct access to electricity and other conventional energy sources.

According to the overall findings, collecting biomass waste is still challenging based on calculated biomass. As a result, the study can inform the decisions and actions of the government, public and private investors, and communities interested in developing renewable energy.

## V. Conclusion

The methodology for bioenergy potential and assessment for energy deployment in rural Vhembe District areas is a complex, comprehensive, and systematic process. It involves identifying potential bioenergy sources, assessing their potential for energy production through a techno-economic analysis, and deploying bioenergy systems such as biogas digesters and biomass gasifiers. The methodology considers a wide range of factors, including the availability of biomass resources, technical feasibility, and socio-economic factors. It is flexible and can be adapted to different settings. Deploying bioenergy technologies can reduce reliance on fossil fuels and promote sustainable and renewable energy sources.

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**Clement M. Matasane** holds a master's degree in electrical and Electronic Engineering from the Cape Peninsula University of Technology (CPUT) and is currently the Research Manager at the Directorate Research Development (DRD) office and was the Grant Coordinator at the College of Health Sciences (CHS), University of Kwa-Zulu Natal (UKZN). From January to March 2017, He completed a six-week University Administration Support Program (UASP) Research Fellowship at Ball State University, Muncie, and Indianapolis, USA, funded by the Carnegie Corporation of New York. An awardee for the UASP Alumni Grant by the International Research and Exchange Board (IREX), USA, for "Implementation of the Online Scholarship System and Research Platforms to enhance research, capacity building, and training project for the CHS." He has four years of experience as an Assistant Director for Research Funding at the University of Botswana, working closely with the School of Medicine and building local and international partnerships and external funding agencies. He has successfully administered projects funded by Botswana, Japan, the United Kingdom, the United Arab Emirates (UAE), Dubai, the United States of America (USA), South Africa, and Zimbabwe collaborated with other researchers, and produced several peer-reviewed publications and conference proceedings.

**Prof MTE Kahn** is the supervisor and leader who guides the research data collection, analysis, and presentation results to ensure that all is according to the research requirements, standards, and university rules.

# CHAPTER 6: Assessment, Modelling, and Estimation of Small-Scale Hydro-energy Potentials

## Article 5: Exploring and Assessment of Small-Scale Hydropower Potentials in Vhembe District Municipality Using Geographical and Spatial Information

Hydropower is one of the most renewable, nonradioactive, and non-polluting sources of energy. Water is pumped from a lower reservoir to a higher one, utilising low-cost dump power produced during periods of low demand by power plants which can be operated economically at a constant load.

Throughout the Vhembe District, the distribution of the river basins and water resources was accessed throughout municipalities, and the capacity of the dams, rivers, and water basins was obtained for the variations of hydro-energy generation. The data maps were used in GIS to evaluate the hydro potentials and possible micro generation.

A GIS analysis was done following the site selection criteria, as were preparation of spatial data and the corresponding layer representing each site, together with preparation of an analysis model, and selection of sites for suitability.

This chapter estimates the hydro potentials for small-scale projects in the areas through modelling and GIS maps. The assessment of the small hydro-power projects for a run-of-river scheme using GIS and maps shows the wide range of significant contributions to hydro-power potential estimation.

# Exploring and Assessment of Small-Scale Hydropower Potentials in Vhembe District Municipality Using Geographical and Spatial Information

CLEMENT MATASANE MATASANE, MOHAMED TARIQ KAHN
Centre for Distributed Power and Electronic Systems (CDPES)
Cape Peninsula University of Technology (CPUT)
Symphony Way, Bellville
COUNTRY SOUTH AFRICA

*Abstract:* - Harnessing the power of water to generate electricity is one of the most cost-effective and sustainable methods of energy production. Small hydropower plants are gaining prominence due to their ability to generate electricity with lower hydraulic heads and smaller flow rates, making them suitable for a wider range of applications. However, the growing global population and its associated demands for water for drinking, agriculture, and industrial purposes are putting increasing pressure on rivers. It is crucial to strike a balance between utilizing river waters for hydropower generation and preserving its availability for essential human needs. The study explored and assessed the small-scale hydropower potentials in the Vhembe District Municipality. The study used geographical and spatial information to identify potential sites for small scale hydropower projects. The study also considered several factors, such as the availability of water, the topography of the area, and the environmental impact of hydropower development. The study found that the Vhembe District Municipality has a significant potential for small scale hydropower development. The study identified several potential sites for small-scale hydropower projects, with minimal environmental impact of the small-scale hydropower development within the area as a viable option and could contribute to the local economy and the green energy transition. The study recommends that the Vhembe District Municipality should further explore the potential for small-scale hydropower development, develop a plan for the sustainable development of small-scale hydropower in the region. The findings can be used to inform the development of small-scale hydropower projects in the region and other parts of the country and being a valuable contribution to the knowledge of small-scale hydropower potential in South Africa.

*Keywords:* - Energy Production, Geographical and Spatial Information, Renewable Energy, Rural Electrification and Development, Small and Micro-hydropower plants, Remote Sensing and Spatial Mappings.

## 1 Introduction

The deteriorating environmental effects, increasing energy demands in the country, migration, and incentives contained in renewable energy policy provide a promising outlook for renewable energy development in South Africa. This has been shown by current energy projects being developed across the country. In emphasis, wind, solar and biomass energy all are derived from the sun, which supplies a constant flow of energy to the earth [1]. In addition, wind, solar and biomass energy are endowed with enormous potential to supply energy. To utilize renewable energy in a scientific manner, the assessment of renewable energy potential and mapping of the spatial distribution of renewable energy potential is the first crucial step.

Considerations of energy efficiency should be integrated at the start of the land use planning process to guide future development of the sites with the best potential for using renewable micro generation. These potentials can be developed in a sustainable way by using multicriteria evaluation methods in a GIS to help optimize new settlements in terms of multi-functionality. There is a history of research using such techniques to support collaborative decision-making processes by providing a framework where stakeholder groups can explore, understand, and redefine decision problems with respect to housing location [2],[3].

South African renewable energy resources have the potential to make a large and vital contribution to the South African energy sector, society, and the economy. In June 2013, Deputy President, Honorable Kgalema Motlante was addressing the delegation and participants of the South African Green Energy Youth Summit in Cape Town where he was a Keynote Speaker. He mentioned that South Africa had intended on developing renewable energy resources not only to diversify the energy mix, without preferring one energy carrier over another, but also to take full advantage of our endowment in other natural resources. He mentioned that with infinite renewable energy resources, South Africa has the potential to become one of the world's fastest growing economic hubs and addressing the environmental impacts and having the sustainable energy resources [4].

In South Africa, renewable energy resources have the potential to make a large and vital contribution to the South African energy sector, society, and the economy for future development of the country.

The Vhembe District Municipality in Limpopo Province, South Africa, has a significant potential for small-scale hydropower systems. The municipality is home to several rivers and streams that have the potential for small-scale hydropower generation that could be used to generate electricity [1],[3],[5]. The municipality is a mountainous topography which provides a lot of potential for headwater hydropower projects. The average annual rainfall in the municipality is 1,000 millimetres that provides a reliable source of water for hydropower generation [2],[4]. A study conducted by the Council for Scientific and Industrial Research (CSIR) in 2017 estimated that the Vhembe District Municipality has a potential of 100 MW of small-scale hydropower [3],[6],[8]. This potential could be used to generate electricity for local communities, businesses, and industries. The CSIR study identified several sites in the Vhembe District Municipality that are suitable for small-scale hydropower projects. Furthermore, a recent assessment of the small-scale hydropower potential in the Vhembe District Municipality found that there are over 1,000 sites with the potential to generate up to 100 kW of electricity [4],[12],[13]. The total potential capacity of these sites is estimated to be over 100 MW, and most suitable sites for small-scale hydropower generation are those that have a minimum head of 10 meters and a minimum flow of 1 cubic meter per second. The most promising rivers for small-scale hydropower generation in the Vhembe District Municipality include the Luvuvhu River, the Shingwedzi River, and the Nwanedi River [5], [8],[9].

Small-scale hydropower projects can be a cost-effective way to generate electricity. They can also be a reliable source of electricity, as they are not affected by fluctuations in the price of fossil fuels. The development of small-scale hydropower projects in the Vhembe District Municipality could have several benefits. These benefits include increased access to electricity for local communities, reduced reliance on fossil fuels, improved economic development and reduced greenhouse gas emissions. In addition, the development of small-scale hydropower projects in the Vhembe District Municipality is a promising way to generate clean, reliable, and affordable electricity. The development would have a significant positive impact on the local community and the environment, and several benefits including improve air quality, increased access to electricity for rural communities, reduced reliance on fossil fuels for electricity generation, increased economic development and creation of jobs in the region.

The other study conducted by the Vhembe District Municipality in collaboration with the Limpopo Department of Economic Development, Environment and Tourism, used a variety of data sources, including topographic maps, river flow data, and environmental impact assessments [6],[12]. The study identified 1,023 sites with the potential to generate up to 100 kilowatts (kW) of electricity and the total potential capacity of these sites is estimated to be over 100 megawatts (MW), which most suitable sites for small-scale hydropower generation are those that have a minimum head of 10 meters (m), and a minimum flow of 1 cubic meter per second [7],[10]. Furthermore, a study by the Council for Scientific and Industrial Research (CSIR) estimated that the Vhembe District Municipality has a potential of 100 megawatts (MW) of small-scale hydropower. This could generate enough electricity to power over 100,000 households. The CSIR study identified several sites in the municipality that are suitable for small-scale hydropower projects, including the Luvuvhu River, the Nzhelele River, and the Olifants River [8],[9] – [12].

Another study, conducted by the University of Limpopo, found that the small-scale hydropower potential in the Vhembe District Municipality is largely untapped [9],[11]. The study found that there are several challenges that need to be addressed to develop small-scale hydropower projects in the municipality. These challenges include the lack of access to finance, lack of technical expertise and environmental concerns [10], [14],[16].

As the results, the assessment of the small-scale hydropower potential in the Vhembe District Municipality is a valuable resource for the development of small-scale hydropower projects in the region [11], [15]. It provides information on the potential sites for small-scale hydropower generation, the technical and environmental challenges of developing these projects, and the potential benefits of small-scale hydropower generation [12].

In this study, all the four municipalities within the Vhembe District Municipality will be assessed to obtain the overall hydro renewable energy potentials map. A spatial tool will be developed in GIS environment to identify the feasible locations for all available hydro renewable energy potentials to assist decision makers in facilitating the decision process for selection.

## 2 Study Area

The Vhembe District Municipality, located in the Limpopo Province of South Africa is shown in Figure 1. The municipality comprises various local municipalities, including Thulamela, Musina, Makhado, and Collin Chabane.

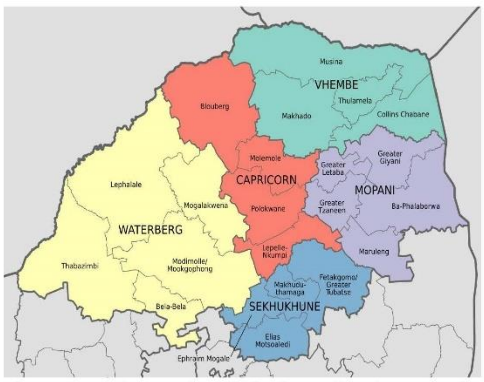


Figure 1. Area view of the Vhembe District Municipality

The assessment will cover the entire municipality to explore and assess the small-scale hydropower potential. The municipality is home to several rivers and streams that have the potential to be harnessed for hydroelectric power generation. The municipality have several potential sites that include Letaba River, Olifants River, Luvuvhu River, Musina River, Shingwedzi River and Mulobezi River, as per Figure 2 in showing the river network data for the municipality as obtained through the remote sensing and spatial mapping.

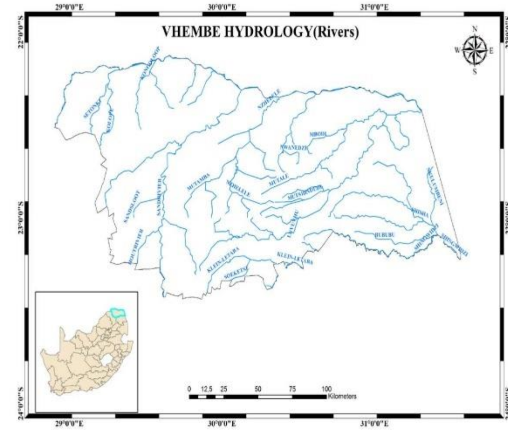


Figure 2. River network data for Vhembe District municipality

These sites have environmental impacts that include changes in water flow patterns, sedimentation, impacts on fish and other aquatic life, vegetation, and visual impacts for tourism. The data from these sources was used to identify potential sites for small-scale hydropower projects and to assess their feasibility.

## 3 Methodology

A geographical and spatial information (GIS) approach was used to assess the SSH potential in Vhembe District Municipality.

The following sources (river network, catchment areas, average annual climate, and rainfall) of data were used for the assessment of the small-scale hydropower potential in the Vhembe District Municipality:

- Environmental feasibility: Characteristics of the environmental conditions and climate in the area.
- Topographic maps: These maps show the physical features of the rivers. They were used to identify potential sites for small-scale hydropower development.
- Hydrological data: This data includes information about the water resources in the municipality, such as the location of rivers. It was used to assess the availability of water for small-scale hydropower development.
- Data collection: Data on rivers, streams were collected from satellite imagery.
- Data analysis: The collected data was analyzed using GIS software to identify potential SSH sites. The analysis considered

factors such as streamflow, head, and catchment area.

## 4 Results

In Figure 3 - 4, shows the average temperature and the duration of the day as characteristics of the environmental conditions and climate change of the area.

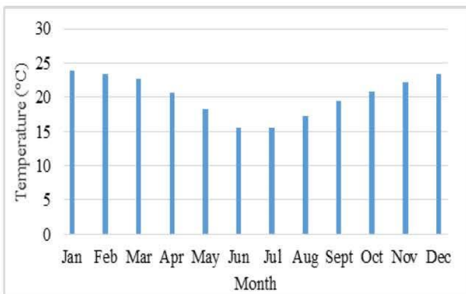


Figure 3. The monthly temperature measurement (Average - 20 °C)

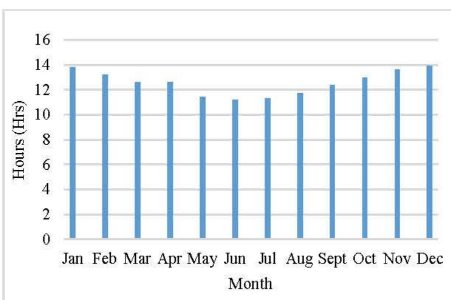


Figure 4. The monthly length of the day measured (Average - 12.5Hrs)

It was noticed that the hottest period is during the months (Jan to Apr and Sept to Dec) and the lowest temperatures are during the months (May, Jun, Jul, and Aug) as applied during the time of different seasons.

Table 1 demonstrates the characteristics of the environmental conditions and climate in the area.

Table 1. Average environmental conditions for the region

| Month | Air Temp. (°C) | Dew Point (°C) | Rel. Hum. (%) | D.S.R. - Direct (MJ/m²/d) | Length of Day (Hrs) |
|---|---|---|---|---|---|
| Jan | 23.9 | 17.4 | 67.2 | 20.6 | 13.8 |
| Feb | 23.4 | 17.7 | 70.2 | 19.6 | 13.2 |
| Mar | 22.7 | 17 | 70.4 | 19.2 | 12.6 |
| Apr | 20.6 | 14.7 | 69 | 20.8 | 12.6 |
| May | 18.2 | 11.2 | 63.6 | 23.4 | 11.4 |
| Jun | 15.6 | 8.1 | 60.8 | 22.3 | 11.2 |
| Jul | 15.6 | 7.7 | 59.4 | 23.3 | 11.3 |
| Aug | 17.3 | 8.6 | 56.5 | 24 | 11.7 |
| Sept | 19.5 | 10.4 | 55.6 | 23.6 | 12.4 |
| Oct | 20.9 | 12.9 | 60.3 | 20.1 | 13 |
| Nov | 22.1 | 15.1 | 64.5 | 19.4 | 13.6 |
| Dec | 23.3 | 16.7 | 66.4 | 19.7 | 13.9 |
| Total Avg. | 20.3 | 13.2 | 63.7 | 21.3 | 12.5 |

During the collected geographical and spatial data for the municipality, the topographic maps obtained show the physical features of the land against the rivers. This hydrological data includes information about the water resources in the municipality, such as the location of rivers. In addition, the river network data shows the location of rivers and streams in the municipality.

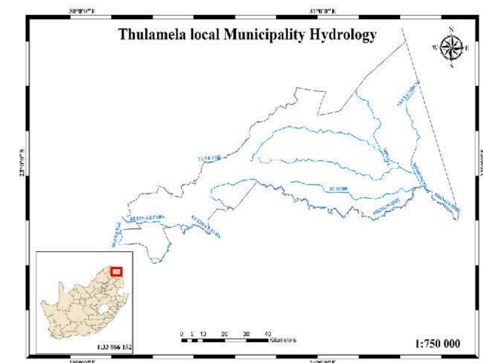


Figure 5. Thulamela local municipality hydrological data

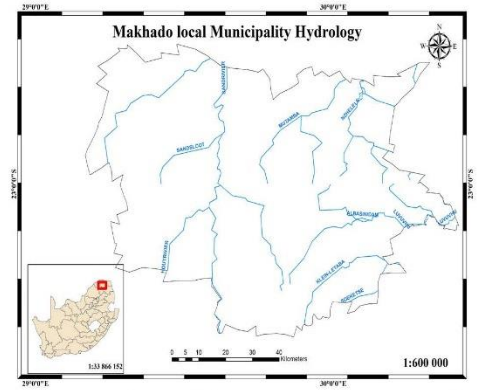

Figure 6. Makhado local municipality hydrological data

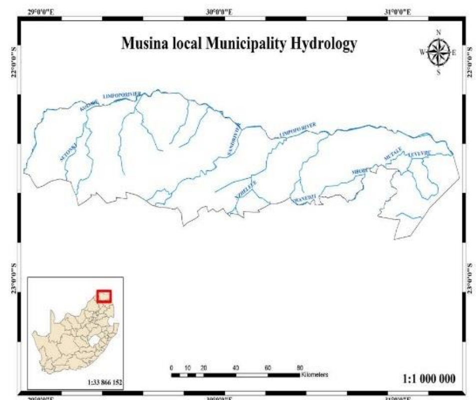

Figure 7. Musina local municipality hydrological data

The data from these sources was used to assess the potential of the small-scale hydropower development in the municipality. The assessment concluded that small-scale hydropower could be a viable option for generating electricity in the municipality, but that it is important to carefully consider variety of factors, including the availability of water resources, the cost of construction, and the potential for environmental impacts.

## 5 Discussion

GIS environments allow the integration of various types of data into a single system. This makes them a powerful tool for multi-perspective analysis over a certain geographic area. The results of this study show that Vhembe District Municipality has significant potential for small-scale hydro development. The Small-scale hydro projects can provide a clean and renewable source of energy to rural and remote communities in the municipality. The small-scale hydro projects can also create jobs and stimulate economic development.

## 6 Conclusion

The purpose of this study was to apply a GIS technology to assess the small-scale hydropower potentials and identify probable hydropower sites in the area for future development. GIS plays a pivotal role in exploring and assessing SSH potentials in Vhembe District Municipality. The application of GIS has led to the identification of numerous potential SSH sites, paving the way for sustainable small-scale hydropower development in the region. GIS-based SSH assessment offers a robust and efficient approach to harnessing the untapped hydropower potential in rural areas, contributing to energy security and economic growth. The results of this study can be used to inform the development of SSH projects in Vhembe District Municipality.

In addition to the factors mentioned above, the following considerations should also be considered when assessing the SSH potential of Vhembe District Municipality:

- Environmental impacts: SSH development can have both positive and negative environmental impacts. The potential environmental impacts of each site should be carefully assessed and mitigated where possible.
- Social impacts: SSH development can also have social impacts on local communities. The potential social impacts of each site should be carefully considered, and mitigation measures should be implemented where necessary.

As the results, small scale hydropower systems are feasible solutions for the region to tackle energy crisis and water challenges for the community. As such, applying environmental knowledge-based and decision-support system approach, it will be possible to integrate, geographical, hydrological, and environmental data to develop a cost-effective small-scale hydropower plant as a solution for supplying low-cost renewable electricity to the rural communities.

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**Institutional Review Board Statement:** Not applicable as the study does not involve humans or animals.

**Informed Consent Statement:** The study does not involve human subjects or any health-related matters.

**Data Availability Statement:** The research data and results are found within the article.

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**Conflicts of Interest:** The authors have no conflict of interest to declare.

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## CHAPTER 7: Assessment, Modelling, and Estimation of Renewable Energy Sources

**Article 6**: Assessment, Estimation, and Modelling of the Renewable Energy Sources using Geographic Information System (GIS) and Remote Sensing (RS) Mapping as a Tool for Renewable Energy Potentials

GIS was used to create a map book combining renewable energy resources (i.e., wind, solar, biomass, geothermal, biofuel, and hydropower). This study shows the potential role GIS plays in renewable energy.

For these reasons, a web based SDSS is a valuable solution to energy resource exploration as it has multiple benefits or capabilities, such as spatial analysis, modeling, decision support, a friendly user interface, and easy access. However, there have been minimal applications. It is still a relatively new research field that integrates GIS, the internet, databases, technical reports, maps, and modeling to create a virtual instrument for a decision support system on renewable energy potentials.

As a result, the methodology used in the wind, solar, hydro, and biomass fields was based on energy estimation. The employed methods evaluated the theoretical, technical, and energy potential in determining the best locations for their potential. In the Vhembe District Local Municipality, Limpopo Province, South Africa, an assessment was conducted utilising GIS mappings tool and remote sensing (RS) data. The outcomes were attained through regionally scaled optimal use of the available renewable options. From the perspective of spatial planning maps, the theoretical potential for solar, wind, hydro, and biomass/biogas energy were calculated and mapped, and data maps provided to identify land suitability to locate the best places for deployment. The study demonstrates the potential applications of GIS for spatial analysis, assessment, modeling, decision support, user-friendly interface, and simple access in the field of renewable energy.

# Assessment, Estimation, and Modelling of the Renewable Energy Sources Using Geographic Information System (GIS) and Remote Sensing (RS) as a Tool for Renewable Energy Potentials in Vhembe District Area, Limpopo, South Africa

CLEMENT MATASANE MATASANE, MOHAMED TARIQ KAHN
Department of Electrical & Electronic & Communication (DEEC)
Centre for Distributed Power & Electronic Systems (CDPES)
Cape Peninsula University of Technology (CPUT)
Symphony Way, Bellville, 7595
REPUBLIC OF SOUTH AFRICA (RSA)

*Abstract:* - Recently, there has been an increase in interest in using alternative, effective, and renewable energy supplies for various power applications in residential, commercial, industrial, and agro-processing settings. To offer communities small-scale production and low-consumption systems, using these renewable resources—which include solar, wind, biomass, hydro, and geothermal systems—has demonstrated a strong interest in providing heat or power at residences in micro-generation. Such technological solutions can improve energy security and supply by encouraging appropriate and sustainable energy sources in communities. The study methodology used in the wind, solar, hydro, and biomass fields was based on energy estimation. The employed methodology evaluated the theoretical, technical, and energy potential in determining the best places for their energy potentials. In the Vhembe District Local Municipality, the assessment was conducted utilizing GIS tools and the analysis of remote sensing (RS) data. The outcomes have been attained through regionally scaled optimal use of the available renewable options. From the perspective of spatial planning maps, they were calculating and mapping the theoretical potential for solar, wind, hydro, and biomass/biogas energy and data maps and identifying the environmental and land suitability to locate the best places for deployment. The study demonstrates the potential applications of GIS for spatial analysis, assessment, modeling, decision support, user-friendly interface, and simple access in the field of renewable energy.

*Keywords:* - Assessment, Estimation, and Modelling; Renewable Energy Sources and Potentials; Solar, Wind, Hydro, and Biomass/biogas; Geographic Information System (GIS) Tool; Remote Sensing and Spatial Mappings

## 1 Introduction

The high significant increase in urban and rural energy demand and the case of deploying renewable energy penetration to the grid makes it inevitable to improve the transmission grid and off-grid systems. Hence, the assessment, estimation, and modeling of the renewable energy sources using Geographic Information System (GIS) and Remote Sensing (RS) as a tool for the Decision Support System (DSS) on renewable energy potentials and optimal is the critical methodology for implementing [1], [3]. The research focuses on the wind, solar, hydro, and biomass/ biogas energy potential and estimation in the Vhembe District Local Municipality, as shown in Fig.1. The purpose was to identify the potential locations of the renewable energy resources and possible application of the small-scale power plants using the Geographic Information System (GIS) and remote sensing (RS) as the tool for the data analysis in the district area. This area primarily comprises rivers applicable to the farmers for people, cattle drinking, and irrigation farming as surroundings of the Mutale, Mbewdi, Tshinane, and Luvuvhu areas. The study domain and characteristics form part of the Limpopo Province by the edge of Botswana, Zimbabwe, and Mozambique through Kruger National Park and divided into four local municipalities, namely, Makhado, Thulamela, Musina, and Mutale [2], [10]. The district is the second lowest access to infrastructure amongst communities in the province. With a high unemployment rate of 53% and a poverty rate of 32%, it is one of the lowest socioeconomic areas in Limpopo Province. The land is very fertile and suitable for agriculture [3]. Many of the lands fall under the tribal authorities [4], [10].


Fig.1: - The topographic Map of the Vhembe Local District Municipality (Source: - Municipal Demarcation Board, 2005)

In assessing and modeling renewable resources, the use of programming systems for renewable energy planning has been considered by taking different approaches. This was through such linear programming seeking to minimize capital investment in new sources, minimize costs of energy flows, or maximize the use of renewable energy [5].

The Geographic Information System (GIS) was used as the tool to create a map book combining Renewable Energy Resources (i.e., wind, solar, biomass, geothermal, biofuel, and hydropower), transmission, parcel, and road data [6] – [9]. The countries can visualize Renewable Energy Resources and transmission lines with the functionality making nearly all facility layouts visual. Locating the right site can be done quickly and accurately with publicly available data and GIS technology. This would help researchers, academics, investors, commercial, industry, private, local, government and developers locate the best renewable energy resource areas in the four municipalities within Vhembe District Municipality to obtain the overall renewable energy potentials maps and weather patterns.

To quantify, assess and model the mapped wind, solar, hydro, and bioenergy potentials, the analyses of land suitability and environment are required to find the optimal locations for deployment of the plants. This paper describes the application of remote sensing (RS) and mapping for energy assessment and the potential use of the *Conceptual Framework for Identification of the Rural Energy Deployment Applications* tool in Fig.2 by supporting the community and the decision-makers in implementing renewable energy projects. The tool helps the decision-makers and communities identify the feasible locations for all available renewable energy potentials suitable for deployment and small-scale energy generations.

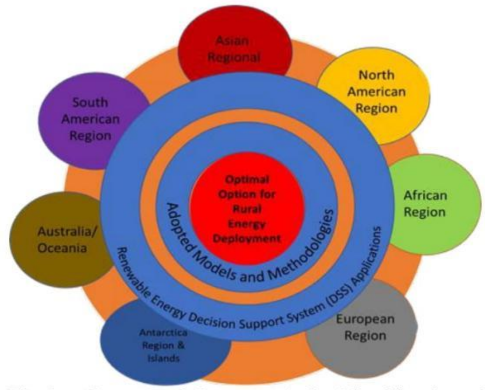


Fig.2: - Conceptual Framework for Identification of the Rural Energy Deployment Applications (Source: Author)

## 2 Experimental and Methodology

The assessment and estimations for possible deployment of the renewable energy potentials focus on the available and acquired data, capacity, yields, access, and optimal locations in deploying these renewable supplies for commercial and domestic use. The analysis for the data sources is conducted throughout the year and harvested from January to December 2018 (that is, daily, monthly, seasonal, and yearly variations during the measurements and recordings) to obtain measurements in determining energy potentials.

The district has four municipalities situated at 22.7696° S Latitude, 29.9741° E 25 Longitude in the Limpopo Province. It is 250m above mean sea level with limited electricity grid access and continuous energy challenges, especially on their socio-economical balance.

To quantify and map wind, solar, hydro, and biomass potential, several aspects must be considered when planning the locations of such power plants [11] - [14]. Different standards and methods are considered when determining the areas of wind, photovoltaic, hydro, and biomass power plants. Thus, to express the geographical potential of wind, solar, and hydro available in the area. Fig.3 and Fig.4 show the status maps from low to high potentials and locations suitable for wind energy deployment and optimal locations. Fig.5 and Fig.6 show the available and potential vegetation and solid-to-waste (biomass) materials found in the district.

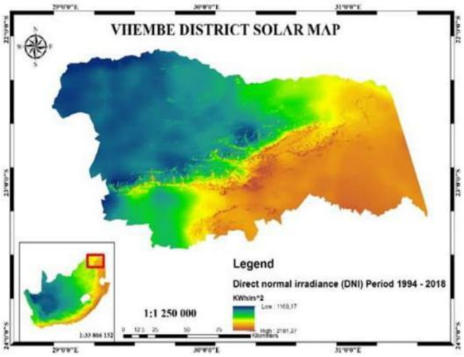

Fig.3: - The Solar Map of the Vhembe Strict Area

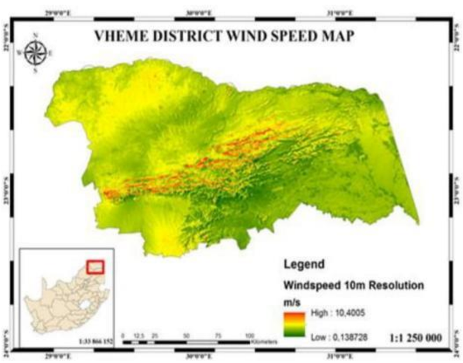

Fig.4: - The wind speed map of the Vhembe District

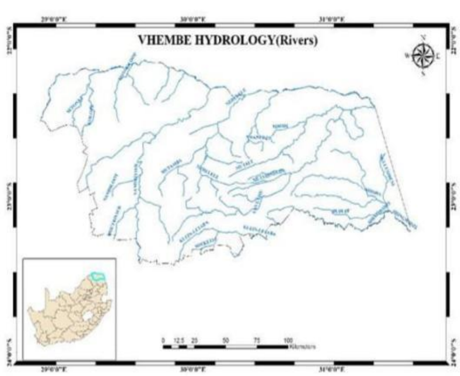

Fig.5: - The hydro map of the Vhembe District

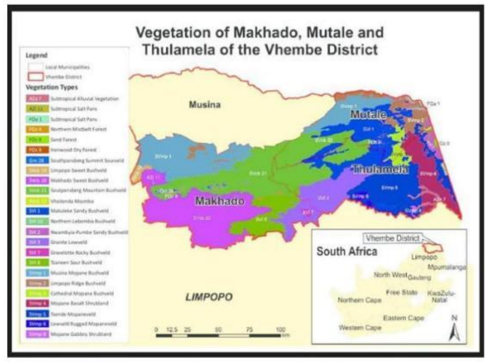

Fig.6: - The vegetation map of the Vhembe District

Different standards and methods are considered when determining the locations of wind, solar, hydro, and biomass power plants. These Several types of restrictions should be considered when positioning power plants in the communities and how one can find the optimal sites for biomass power plants and suitable areas for wind and PV power plants. Remote sensing and mapping were used in obtaining the wind, solar, hydro, and biomass maps. The wind variations referenced to the 10m height were obtained to determine the wind potential with the use of the kinetic energy flux for the total available energy in providing to the wind turbines to generate electricity, with the estimation that it will be operating at optimal efficiency.

The Vhembe district was selected as it forms part of the rural area that constitutes major agricultural activities which also use water irrigation for communities and farming. In addition, all the water and rivers were captured from upstream and downstream in the area for the potential and availability for domestic and commercial use. These were captured using the GIS remote sensing and mapping tool, similarly to the wind and solar potentials. The duration, directions, and frequency distribution were exploited in assessing the wind availability for the power generated at the sites on the installed weather stations and permittable wind machines to be installed.

In measuring the solar radiation and its potential for photovoltaic applications in the area, the primary solar irradiance measurements and solar radiation intensity were predicted and determined from the installed weather stations and data acquisition of the meteorology data through the computational solar analysis using Matlab.

Biomass power generation is a crucial component of the energy mix in a developing nation like South Africa. Rural communities, especially in the Vhembe

District, will be lifted out of poverty and move towards a wealthy and equal future by using biomass as a means of the energy system. Access to affordable, reliable energy is essential for sustainable growth on both an economic and environmental level, as the most prevalent crops in the district in terms of biomass are mangos, oranges, apples, litchi, banana, and sugar cane, which are produced in the large quantities as an agricultural area. There are many different estimates of the total biomass capacity with the leading agricultural crop in the area that can be processed to provide electricity from the leftovers and waste on farms.

There is a high potential for the biogas digesters to turn waste, such as kitchen scraps and cow dung, into methane gas that can be used for cooking and heating. Biomass can be supplied by dedicated agricultural crops of arboreous and herbaceous species such as annual crops (corn, soy, sunflower, and sorghum).

As several models for biomass and biofuels have been developed to support the decisions over which species to grow, the local climate, morphology, soil characteristics, water, and nutrient needs are commonly used to identify the set of species suitable for a specific area [15].

## 3 Modelling and Simulation

Measurements were remotely captured throughout one entire year. The data acquisition (DAQ) system was used to obtain data from the nine Weather Stations (WS) used during the data collection (i.e., Hanglip, Shefeera, Tsianda, Thohoyandou WO, Dzanani Biaba Agric, Mphefu, Joubertstroom Plantation, Vondo - Bos and Tshivhasie Tea Venda). This was to determine the annual weather changes and patterns for the ranges during the yearly session, as shown in Fig.7 and Fig.8.

As the results, within reference to the measurements obtained, the data was used to determine the solar energy potential for the Vhembe District at specified locations to evaluate its amount for power generation. The assessment and estimations for possible wind energy deployment focus on the 10-meter height allowance for typical wind farm systems, data assessment, capacity, annual energy, and energy outputs. The weather conditions and data sources were harvested from January to December 2018 (daily, monthly, seasonal, and yearly variations during the measurements and recordings) to obtain average wind measurements to determine wind potentials. Various measures were conducted and recorded in determining the wind speed potential in the Vhembe District to estimate its energy potential, as Fig.9 illustrates.

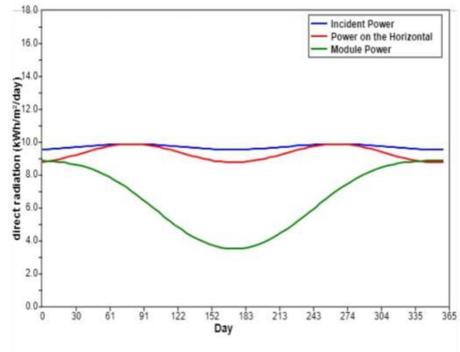


Fig.7:- The daily incident power generation per direct intensity

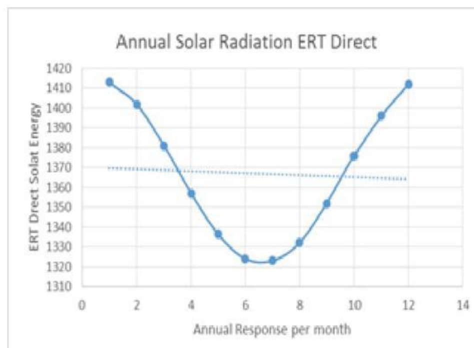


Fig.8: - Energy trends for Solar Radiation in Vhembe District

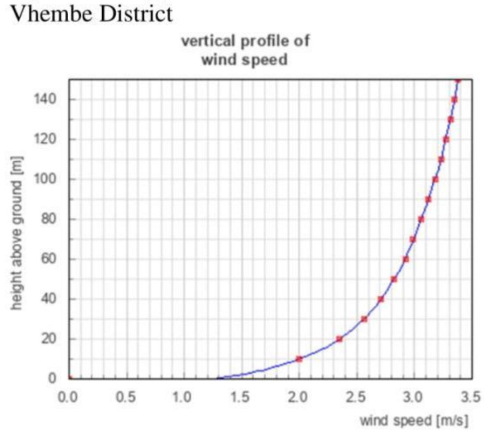


Fig.9: - The wind profile speed is under 10m height above the ground.

## 4 Results and Discussions

This method would be carried out with ARGIC GIS Software tools, techniques, and demand-supply matching tools on all the renewable energy resources. The Microsoft Visual Basic and Webcast tools will be used in the database for the development of the framework model. Once all data collection has been achieved, the demand on energy potential and its profile will be established and analyzed for optimal energy uses at present and at the identified site. All stages will be conducted by collating data to achieve optimal demand supply. These would be carried out in all the energy potentials through the GIS-based energy tool for solar, wind, biomass, and hydro system. Adopting the methodology would be helpful and realistic for implementing microgeneration energy technologies. The data demand would be accessed from all the Vhembe District Councils. The Google Earth Map and database will be used to gather the geographical data for the potential sites and other databases such as SAWA, NREL, ERENA, and NASA metrology databases. The data required for the renewable energy evaluation is shown in Table 1. In addition, the comprehensive site selection for the proposed solar, wind, biomass, and hydro generation plants should be followed by the environmental and economic feasibility criteria as demonstrated by the obtained results from Fig.3 to Fig.9.

Table 1: - Content for the vector data sources required for renewable energy potentials

| Data | Data format |
|---|---|
| Solar, wind, biomass, and potential hydro atlases | MapInfo |
| Forest areas | MapInfo and Geodatabase |
| River/ water basin areas | MapInfo and Geodatabase |
| Agricultural (i.e., fruits and crops) areas | Geodatabase |
| Farmers areas | Geodatabase |

The data measurements of the global solar radiation to be used are directly from locations where data is taken from the extra-terrestrial radiation and metrology data during the sunshine and cloudiness as empirical data. As a result, the thematic maps will be generated from the GIS to access the availability and variation of global solar radiation. As such, the solar potential will be identified for the specific area or location. The data will include temperature, relative humidity, rainfall, and hourly sunshine for the sites, as illustrated in Fig.7 and Fig. 8.

The wind energy potential will be determined by calculating the annual average wind speed for a specified location. This wind speed is obtained from the SAWA metrological data and local government. It will be grouped into seasonal times such as winter, summer, spring, and autumn to analyze and assess the wind data. The maps will be generated through the ARGIC GIS to help identify the most and the least suitable potential wind energy mappings, as shown in Fig.3. The constraints, such as topography, wind speed, and direction, will not be considered.

Hydropower is one of the most renewable, nonradioactive, and non-polluting sources of energy. Water is pumped from a lower reservoir to a higher one, utilizing low-cost dump power produced during periods of low demand by a power plant that can be operated economically at a constant load. Throughout the Vhembe District, the distribution of the river basins and water resources can be accessed by the municipalities, and the capacity of the dams, rivers, and water basins would obtain for the variations of hydro energy generation. These data will be used to be implemented in GIS to evaluate the hydro potentials and possible micro generations.

The biomass or bioenergy potentials will be assessed through compilation and computation of the bio-resource supply of all the available waste, agricultural residue, fruits and crops, forest, horticulture residue, plantation and livestock dung, and municipal wastes. The data to be used for these bioenergy resources will be collected from the Department of Agriculture and Forestry, Department of Waste Management and Sustainability, and the Vhembe District Municipalities. Implementing in GIS, the bioenergy availability maps and statistic data will represent the thematic maps of the total biomass or bioenergy potential in the location identified. Fig.6 shows the workflow for the bioenergy data collection methodology and the potential analysis in GIS.

It is observed that the availability of the biomass in the district is mainly on the use of biomass being degraded into biogas as the potential technology suitable for using the cow dung, chicken manure, organic waste (banana, orange, mango, litchis, apples, oranges, and vegetables) as the substrates popular as means of economical uplifting by the communities and the farmers. Furthermore, over the area, the waste is the traditional biomass used for cooking and heating in most rural communities, which are dominated by poor households with limited or no access to energy services. This deficiency of access to energy services drastically affects economic production but is also a critical basic service such as health care and education challenges in the area.

## 5 Conclusion

GIS is used to create a map book combining Renewable Energy Resources (i.e., wind, solar, biomass, geothermal, biofuel, and hydropower), transmission, parcel, and road data. The countries can visualize Renewable Energy Resources and transmission lines with the functionality making nearly all facility layouts visual. Locating the right site can be done quickly and accurately with publicly available data and GIS technology. This would help investors and developers discover the best renewable energy resource areas. This study will show the potential role GIS plays in renewable energy.

For these reasons, a web based SDSS is a valuable solution to energy resource exploration as it has multiple benefits or capabilities, such as spatial analysis, modeling, decision support, a friendly user interface, and easy access. However, there have been minimal applications, and it is still a relatively new research field by integrating GIS, the Internet, databases, technical reports, maps, and modeling to create a virtual instrument for the decision support system on renewable energy potentials for the region.

However, there are alternatives to traditional biomass, such as biogas technology, which can provide clean and reliable energy services.

This study assessment technique is a model for estimating the potential effects of the available renewable resources, climate, environment, landscape, and possible change on the livelihood of the specified area. It also highlights the methods for understanding climate change in the district.

Solar – The assessment and estimation model using the weather data, GIS maps, and environmental conditions are the most recent data measured from (January to December 2018) of the meteorological data obtained in the nine installed weather stations. The duration, seasonal and annual analyses have been presented in this work. The high solar radiation was recorded from January to April and September to December, while the lower solar radiation was recorded from April to August month. As the results, the analysis demonstrates that the required solar radiation values for the potential use in the field are estimated by the geological environment and temperatures commonly measured by the installed weather stations around the Vhembe District. As such, the obtained results can be employed as the best exemplar for solar estimation at different geographical locations and climatic locations. A location's suitability for maximizing solar energy received and power generated at the chosen position must be determined to obtain the optimal and prospective PV radiation.

Wind – The wind energy potential in the Vhembe District area concluded with the following assessments: - It was found that most wind energy systems in the district were used for water pumping in rural areas for small farming and domestic use. Locating the right site can be done quickly and accurately with publicly available data and GIS and Remote Sensing technology as obtained in the study. This would help communities and decision-makers, as well as investors and developers, in locating the best location for wind energy resources in the district. The presented estimation and modeling of wind energy is a valuable tool in wind energy assessment and power estimation for domestic and small farmers to benefit economic energy applications. The wind data obtained has been used for wind estimations, assessment, calculations, and modeling as was conducted through nine installed Weather Stations (WS).

Biomass – In today's fast-paced society, alternative fuel alternatives are essential. To replace fuel, which is required in households and businesses, we must develop a sustainable renewable energy source. Biomass, which comes in many forms, is necessary for biofuel. We will always have a fuel alternative if there is animal and plant waste. It will be necessary to increase the growth of feedstock and the effectiveness of conversion routes if biomass energy is scaled up to a level where it can influence the world's emissions of greenhouse gases. A biorefinery system's capacity to remain economically viable can be significantly impacted by quantifying and planning for the uncertainties included in a biomass feedstock supply system.

Building reliable supply system designs that can survive a multitude of unknowns requires an understanding of uncontrollable variabilities, such as weather conditions (bale moisture, crop production) and their impact on feedstock logistics.

Hydro – In addition, in the study, we developed a model for evaluating the hydropower potential with the purpose of supporting decision makers and energy planning to directly consider all variables in a GIS environment accounting for their spatial variability and including information such as the distance from urban areas, or the dependency of civil engineering works costs on land use. Consequently, this study will be helpful to the authorities in developing potential water resources in the district for hydropower generation in support of improving the electricity generation for small-scale farmers and communities. As a result, the GIS software can help identify sites with hydropower potential using several datasets and potential sites for mini and small hydropower deployment. Finally, as there is currently, about 57% of the population in Sub-Saharan Africa does not have access to electricity. The rapid electrification efforts would assist in decentralized hydropower as an effective solution for rural electrification, especially when its deployment was the result of structured and well-informed action plans. Similarly, small-scale hydropower can be a plausible electrification option in today's electrification challenge. To that end, proper planning is essential, and so are new data and tools that can better inform electrification policy.

## 6 Acknowledgment

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**Author Contributions:**

MTE Kahn is the supervisor and leader who guides the research data collection, analysis, and presentation results to ensure that all is according to the research requirements, standards, and university rules.

## CONCLUSION

The methodology employed on assessing, estimating, and modelling renewable energy potential in this study does not have any limitations and can be used in any study area or on any concept adopted by decisions-makers and investors in analysis for identifying new potential locations for power generation. In addition to assessing wind, solar, hydro- and biomass energy potential, the methodology integrates climate and environmental resources, remote sensing, and spatial geographical conditions in evaluating the characteristics of the four variable types of renewable energy potential.

Based on the results and the current situation of renewable energy development in the study area, suggestions and advice are provided for renewable energy planning in the future and for the policy makers and developers for informed decisions on potential projects. As a result, the estimated results during the study, and the assessed potentials still can be exploited, as wind, solar, hydro-and biomass potential provides adequate parameters for spatial analysis for possible energy resources in the region.

The district is situated in an excellent solar radiation area with terrain that describes wide spatial distribution of solar radiation in this study area which can generate a good energy supply for commercial and domestic applications.

The land suitability and potential analysis of small wind power plants assessed in the area indicates that the location is acceptable and adequate to install wind capacity that can cater for small farmers and communities.

However, with the existing biomass resources, challenges exist regarding the collection and distribution of biomass residue. To improve biomass residues for possible continuous biomass supply, farm owners and municipalities must enter into agreements to guarantee continuous transportation of biomass residues for sufficient supply to stimulate biomass energy development at the potential location.

In addition, problems in renewable energy development have been pointed out for wind, solar, hydro, and biomass energy separately, and possible solutions have been provided as there is still more interest from the researchers in the potential for a new field of study, though limitations still exist.

This research found that the potentials for solar, wind, hydro- and biomass energy vary at different locations across the Vhembe District, Limpopo. This study contributes to the overall research project on RS and mapping for energy assessment and the potential use of the Conceptual Framework for Identification of the Rural Energy Deployment Application tool in supporting the community and decision-makers in implementing renewable energy projects. As such, the tool and application of the multi-criteria decision making and assessment in the district provides the achieved objectives as intended through:

1. Examining and presenting the energy status through solar radiation estimations using territorial climatological measurements and the conditions in the GIS map as the necessary conditions for such projects.
2. Assessing and presenting the available yield of wind energy potentials considering environmental and land use in exploitable areas of the wind resources.
3. Modeling the energy scenarios and developing specific recommendations and improving the planning of future projects on biomass energy potentials.
4. Estimating the hydro potential for the small-scale projects in the area through modeling and GIS maps.
5. Providing a summary of the GIS tool in all the renewable energy applications (that is, solar, wind, biomass, and hydro) that are suitable for assessing, estimating, and validating each energy potential for utilisation and deployment as the solution for communities, designers, and installations.

In the Vhembe District Local Municipality, the assessment was conducted utilising GIS tools and the analysis of RS data. The outcomes have been attained through regionally scaled optimal use of the available renewable options. From the perspective of spatial planning maps, the theoretical potentials for solar, wind, hydro, and biomass/biogas energy were calculated and mapped to create data maps, to identify environmental and land suitability, and to locate the best places for deployment.

For these reasons, this is a valuable solution to energy resource exploration as it has multiple benefits or capabilities, such as spatial analysis, modelling, decision support, a friendly user interface, and easy access. However, there have been minimal applications, and it is still a relatively new research field to integrate GIS, the internet, databases, technical reports, maps, and modeling to create a virtual instrument for a decision support system on renewable energy potentials for the region.

## FUTURE WORK

With the presented geographical information method, the researcher has achieved the three major research objectives, namely (1) to quantify and map wind energy, solar energy, hydro- and bioenergy potential; (2) to define an environmental understanding of wind, photovoltaic, hydro and biomass power plants; and (3) to analyse land suitability for wind, hydro, and photovoltaic power plants and to find the optimal locations for the power plants. Based on the research results, suggestions for renewable energy development in the future have been proposed for the advancement and improvement of quality of life. Nevertheless, the research still has some limitations that could be improved with further study.

The wind speed data used to estimate wind energy potential and the temperature data used to assess the solar resources are from 8 meteorological stations, but if more meteorological data is required, there are national meteorological stations available free of charge, which could be used for further estimations. To improve the precision of the output, more meteorological data from provincial meteorological stations or municipal meteorological stations should be obtained to expand the study or for further analysis.

Although the land cover data provide detailed information about vegetation classes, detailed information about farmland classes, specifically identifying fertile and barren land, should have been classified in this study, as renewable energy power plants should avoid fertile farmland. The lack of farmland classification leads to imprecise land suitability analysis results.

PV technology and direct combustion were selected to evaluate solar energy potential and biomass potential respectively, but other technologies exist in addition to these. As the technical potential of renewable energy varies with the technologies used, identifying the type of technology that maximises renewable energy potential is an open research question for future study.

In the economic potential assessment, transmission line cost is not included due to the lack of current transmission line data. However, in renewable energy projects, transmission line costs account for a large percentage of the investment cost. For further study, transmission line costs should be considered in the economic potential assessment.

Combining renewable energy with conventional energy offers additional opportunities for utilising renewable energy. Solar power plants can be built with coal power plants. During winter, coal power can supplement solar power.

Similarly, biomass power plants could be combined with coal power plants to solve the problems of interruptions to biomass residue supply.

This research is the first effort to assess renewable energy potential based on GIS in this study area. The study includes the development of an overall method of estimating renewable energy potential while considering climate resources, geographical conditions, technology characteristics, economic factors, and renewable energy policies. With enhanced data quality, various renewable energy technologies and combinations with conventional energy, further studies in the field could bring a greater number of promising benefits for the country and contribute to the study context.

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## Appendix 1. - Exploring the Sustainability and Perspectives of the renewable Energy Policies and Economic Development on Ecological Footprints

This article was written in collaboration with international partners as part of my doctoral journey in contributing to the energy mix and nexus on exploring the sustainability and perspectives of the renewable energy policies and economic development on ecological footprints.

sustainability

MDPI

Article

# Exploring the Impacts of Renewable Energy, Environmental Regulations, and Democracy on Ecological Footprints in the Next Eleven Nations

**Jintian Wang [1], Shouchang You [1], Ephraim Bonah Agyekum [2], Clement Matasane [3] and Solomon Eghosa Uhunamure [4,*]**

[1] School of Economics, Shandong University of Technology, Zibo 255000, China
[2] Department of Nuclear and Renewable Energy, Ural Federal University Named after the First President of Russia Boris Yeltsin, 19 Mira Street, 620002 Ekaterinburg, Russia
[3] Faculty of Engineering and Built Environment, Cape Peninsula University of Technology, P.O. Box 652, Cape Town 8000, South Africa
[4] Faculty of Applied Sciences, Cape Peninsula University of Technology, P.O. Box 652, Cape Town 8000, South Africa
* Correspondence: uhunamures@cput.ac.za

**Abstract:** Economies are making environmental regulations to achieve sustainable development and mitigate environmental pollution. However, these regulations cannot provide effective results unless implemented properly. The role of the government is fundamental in this regard. In this context, this research probes the impacts of democracy, environmental regulations, renewable energy, globalization, and economic growth on ecological footprints in N-11 countries from 1990 to 2018. For statistical analysis, this work applies the cross-sectional autoregressive distributed lags (CS-ARDL) methods. This method efficiently provides robust findings for panel time series data because they counter the cross-sectional dependence and slope heterogeneity while providing the results. Moreover, augmented mean group (AMG) and fully modified ordinary least squares (FMOLS) are used to check the robustness of the findings. The results show that environmental regulation significantly mitigates ecological footprint, while economic growth escalates footprints in N-11 countries. In addition, democratic quality, renewable energy consumption, and globalization are contributing factors to environmental quality. Hence, this research presents important policy implications for the N-11 countries in that they need to enhance democratic accountability. This will assist them to launch an effective environmental policy. Effective environmental policy will assist in increasing renewable energy, which will ultimately enhance the environmental quality.

**Keywords:** democracy; environmental regulations; environmental sustainability; renewable energy; N-11 countries

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## 1. Introduction

Today, the world is facing drastic environmental problems and no country is being spared from the associated changes. Several studies have documented that unsustainable consumption represents the main driver of climate change [1,2]. Unsustainable consumption is not astonishing for developing countries. Developed countries are also facing climatic problems. The demand for food, water, and energy is increasing, due to which biocapacity is decreasing in these countries [3,4]. Besides that, N-11 countries are among those countries whose ecological deficit is rising continuously. Therefore, it is important to measure the factors of ecological deficit in these nations because they are contributing to the world's economic development. To deal with environmental problems, N-11 countries have established many environmental regulations. Figure 1 shows the trends of patents on environmental technologies in N-11 nations. The number of patents shows the research and development in a particular country. This activity can be enhanced if the quality of education is good and equal opportunities are provided to all citizens. The trend of patents is almost changing similarly in these countries, but the number of patents can be varied due to the diverse economic growth and population growth.

Despite the efforts to improve their environment, these countries are investing in non-renewable energy (RE) sectors, especially after the COVID-19 pandemic.

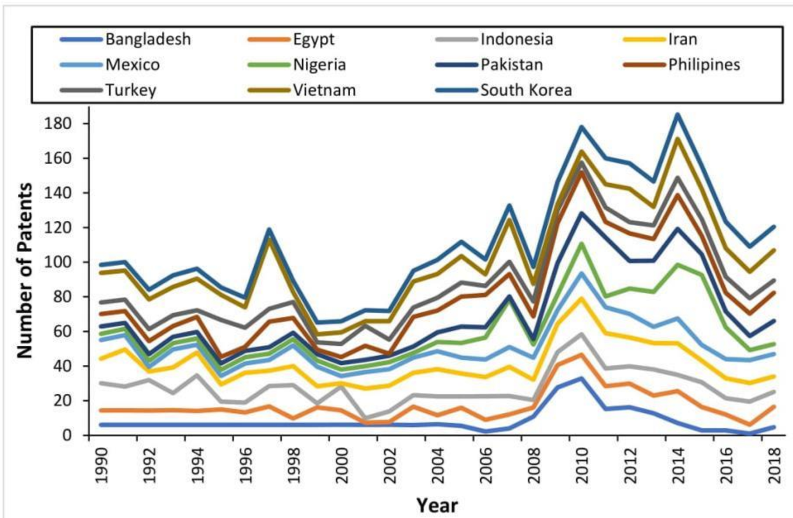


**Figure 1.** Patents on environmental technologies.

This work aims to investigate the impacts of environmental regulations (ER) and democracy (DEM) on ecological footprints (EF) in N-11 nations. This work adds other important factors of (RE) economic growth (GDP) and globalization to the model. Energy plays a fundamental role in economic development, but if this energy is from fossil fuels, it will degrade the climatic quality [5,6]. To curb the ecological deficit, different countries can promote efficient energy, but this energy may provide limited benefits. To reduce ecological footprints, it is important to move towards cleaner energy. These cleaner energy sources of solar, wind, and hydropower can boost economic growth and create environmental sustainability [7,8]. Countries must design environmental regulations to promote greener technologies and effectively manage waste. ER can reduce environmental pollution by bringing efficient sources of energy production. These efficient resources can boost greener technologies that increase economic growth without hurting the climate [9]. On the other side, flexible environmental regulations can bring dirty technologies for energy production that can pollute the climatic quality [10]. Therefore, in this era of globalization, countries with flexible environmental laws import more carbon than their partners with strong environmental regulations [9]. Xiaoman et al. [11] said that globalization is mitigating the environmental pollution in the countries that have strict environmental regulations.

ER may not provide the desired results due to poor implementation. In this context, Omojolaibi et al. [1] cannot find an effective role of ER in the MENA region to reduce EF. Therefore, it is valid to enquire about the role of ER towards environmental pollution. It is also essential to probe the role of democracy because democracy controls environmental regulations. Several studies have documented the role of democratic accountability toward ecological sustainability in many ways. For example, media and freedom of speech increase public awareness about environmental pollution [12]. This environmental awareness further pressurizes the government for strict environmental regulations. These strict environmental regulations further create environmental sustainability [13]. Moreover, democratic systems create more accountability and public participation [14]. This kind of accountability ensures the implementation of ER and reduces corruption. On the other side, the economies may focus on economic development rather than on ecological ones. Democracy is considered to have strong connections with the economic prosperity of the people and this economic growth may degrade the climatic quality. Hence, in line with the modernization theory, democracy may degrade the climate [15].

The research works that investigated the associations of ER, democracy, and ecological footprints are very few with contradictory results. For example, Omojolaibi et al. [1] found that democracy is degrading the climate in the MENA region, but the work by Murshed et al. [9] proved that ER is improving air quality in south Asian countries.

This work has chosen the next eleven countries for analysis because these countries are among the leading economies that significantly contribute to the world's GDP.

Goldman Sachs investment bank identified these countries as having the potential to become the largest economies in December 2005. The bank selected these countries on the basis of factors, including economic stability, political maturity, investment policies, trade openness, and education quality. Although these countries varied in terms of geography and economy, one thing that connects them is their high potential for economic growth and huge, growing population. Therefore, considering their economic potential, it is important to investigate the factors of ecological footprints for effective policy instruments in the future.

However, in pursuit of rapid economic growth, these countries compromised their natural environment, which is evident from their increasing ecological footprints. These countries have been actively engaged in globalization activities for the last few decades. In this context, these countries are promoting environmental innovation and a renewable energy transition to overcome ecological degradation and biodiversity loss. Considering the increasing role of globalization and ecological footprints, it is important to explore the impacts of globalization and RE on ecological footprints. The role of environmental regulations is essential for a cleaner environment and a system of government can shape the environmental regulations. Therefore, this work also includes democracy and environmental regulations in the model for N-11 nations. The effect of these variables on ecological footprint is still unclear.

In this background, this work contributes to the literature in three ways. Firstly, this work explores the linkages of environmental regulations, democracy, and ecological footprints in N-11 countries in the occurrence of renewable energy, economic growth, and globalization. The long and short-run linkages have been probed in this work because the authors have not seen any work for N-11 countries. Secondly, this work presents the estimations from the methods of cross-sectional autoregressive distributed lag (CS-ARDL), fully modified ordinary least squares (FMOLS), and augmented mean group (AMG) to compare the findings. CS-ARDL is a second-generation method and provides short and long-run coefficient values. This method also provides the error correction term (ECM), which shows the stability of the model. The AMG method is an efficient method that includes the CD in the panel data and provides coefficient values. Thirdly, this study has taken ecological footprints as a proxy for environmental pollution. EF presents a holistic approach to studying environmental pollution as a sum of soil, air, and water pollution [2,16]. On the other side, $CO_2$ emissions capture energy-related pollution only [17]. Therefore, this work is utilizing the guidelines of recent literature in taking EF as a proxy for environmental pollution.

## 2. Literature Review

Previous studies have documented the impacts of ER on EF from different perspectives. For example, Danish et al. [18] used the FMOLS method to investigate the impacts of ER on $CO_2$ emissions in BRICS. They validated the environmental Kuznets curve (EKC) and found that ER is reducing $CO_2$ emissions. Wenbo et al. [19] found that ER mitigates air pollution in Chinese provinces, but this association is subject to regional variations. They also validated the EKC in 30 Chinese provinces.

Yang et al. [20] found that ER is linked with the companies that are relocated in the areas with weak ER in China. They found that different areas responded differently to different ER. For OECD countries, Hashmi et al. [21] used random and fixed effect models and found that ER reduces $CO_2$ emissions. On the flip side, Wang et al. [22] showed that innovations are increasing the $CO_2$ emissions due to rebound effects. Moreover, ER can slow down economic growth in developing nations. Pei et al. [23] reported that ER not only lowers $CO_2$ emissions, but also enhances environmental quality through efficient technologies. Zhang et al. [24] found that ER is improving air quality in China at the national level, but the unification of ER and industrial production is useful in some regions and not useful in other regions. Zhao et al. [10] found that ER helps to reduce $CO_2$ emissions and it is also helping in making energy-efficient resources in China.

Considering the EF and ER connection, Murshed et al. [25] said that ER is reducing EF in south Asian countries due to renewable energy consumption. Omojolaibi et al. [1] said that economic growth and energy use are degrading the climate, but ER does not affect EF in the MENA region. Shahzad [26] studied an inclusive literature survey to know the ER and EF linkages. They found that this association is still ambiguous and needs more scrutiny. Wang et al. [27] argue that market-oriented environmental regulation tools can play a pivotal role in improving the green total factor energy efficiency, which improves the environment. Ahmed et al. [28] probed the linkages of economic complexity, democracy, and RE budgets on EF over the years 1985–2017 in G-7. They found that democratic accountability is increasing EF, but that RE and financial development curb EF. Huang [29] found that communication technologies, economic complexities, and human capital contribute to more environmental pollution. RE is improving air quality in G-7 nations. Addai et al. [30] investigated the impacts of urbanization and economic growth on EF in eastern Europe. They pointed out that urbanization and economic growth are reducing EF. Qin et al. [31] validated EKC in G-7 nations. They found that composite risk index and green innovations improve air quality. Abbas et al. [32] investigated the impacts of RE, non-RE, transport, and urbanization on $CO_2$ emissions in Pakistan. They found that urbanization, transportation, and non-Re are degrading the climate.

At the same time, several studies investigated democracy and EF linkages. Güngör et al. [14] applied the pool mean group (PMG) method to nine countries and found that democracy (DEM) mitigates $CO_2$ emissions. Moreover, Adams et al. [33] found that DEM and renewable energy (RE) lowers $CO_2$ emissions in African countries. Murshed [34] documented that DEM lowers deforestation and helps to validate the EKC in Bangladesh. Akalin et al. [15] said that DEM is increasing EF in OECD countries but RE is increasing environmental quality. Shao et al. [35] examined the impacts of green innovations and RE on CO2 emissions in N-11 nations. RE and green innovations are important for a cleaner environment. Agheli and Taghvaee [36] found that there is a connection between political stability and the environment. Li et al. [37] found that environmental accountability can lower the environmental pollution in China. Banik [38] found that democracy can bring sustainable development effectively. Zhao et al. [39] found that green technology is an effective factor that can lower ecological footprints.

From the above arguments, the impacts of ER and DEM on EF are scant. Different studies have found contradictory findings and the literature on this topic is inconclusive. Therefore, this study investigates the impacts of DEM and ER on EF in the panel of N-11 countries.

## 3. Theoretical Basis, Data, Model, and Methodology

Today, developed and developing countries are facing the problems of environmental pollution. In efforts to mitigate the environmental pollution, nations are striving for clean energy production. Governments are increasing the research and development projects by approving special budgets through regulations. A fair and transparent regulatory body is essential to launch transparent regulations. In this regard, it is important to analyze the linkages of renewable energy production, environmental regulations, and democracy on ecological footprints.

This paper investigates the impacts of democracy (DEM), environmental regulations (ER), renewable energy (RE), economic growth (G), and globalization (GL) on ecological footprints (EF) in N-11 countries (Egypt, Bangladesh, Iran, Indonesia, Nigeria, Mexico, Philippines, Pakistan, South Korea, Turkey, and Vietnam). This work adopts the EF as a proxy for environmental pollution. Unlike $CO_2$ emissions, EF takes environmental pollution from a holistic approach. EF considers the soil, wind, and water pollution (current). Economic growth is well known for its contribution to ecological degradation because it requires huge energy [40]. However, RE provides an important substitution for energy usage and it contributes to economic growth [8]. Nevertheless, nations implement effective ER for energy efficiency [26]. ER not only curbs environmental pollution but also increases the RE for economic growth. The ER is implemented by political institutions. Democracy is an important political condition that increases freedom of speech through media and enhances environmental awareness. Therefore, democracy makes the citizens pressurize their governments for strict environmental regulations. The implementation of strict environmental regulations further improves environmental sustainability [13]. Finally, globalization can import energy-intensive technologies that can pollute the climate because bilateral trade can import dirty technologies to developing countries with flexible environmental regulations [9]. On the other side, globalization can also lower the *EF* by importing efficient technologies [41]. The data concerning *EF* were obtained from the global footprint network. The data on *RE* and GDP were obtained from the World Bank. Environmental regulations, democracy, and globalization data were obtained from the OECD, ICRG, and KOF institute, respectively. Hence, considering the above discussion, the following will be the model for this work:

$$lnEF_{it} = f(DEM_{it}, ER_{it}, G_{it}, GL_{it}, RE_{it}) \quad (1)$$

where *EF* is ecological footprints in global hectors, *DEM* is democracy measured by the democratic accountability index, *ER* is environmental regulations calculated by the patents related to environmental technologies, *G* is economic growth, *GL* shows globalization (overall index), and RE is renewable energy (% of total energy). Table 1 shows the variables, their description, and sources.

**Table 1.** Data description and sources.

| Variables | Symbol | Unit | Source |
|---|---|---|---|
| Ecological Footprints | EF | Global hectare per capita | GFN |
| Renewable Energy use | RE | % of total Energy consumption | WDI |
| Gross Domestic Product | GDP | Constant US dollars | WDI |
| Environmental regulations | ER | Patents related to environmental technologies (% of total) | OECD |
| Democracy | DEM | Democratic accountability index | ICRG |
| Globalization | GLO | Overall globalization index | KOF Index |

All the data is transformed into their log form. Log form increases the sharpness of the data and provides robust results [42]. The log form of equation is as follows:

$$lnEF_{it} = a_0 + \beta_1 lnDEM_{it} + \beta_2 lnER_{it} + \beta_3 lnG_{it} + \beta_4 lnGLO_{it} + \beta_5 lnRE_{it} + \epsilon_{it} \quad (2)$$

This work utilizes the annual data of 1990–2018 for all variables. The data before 1993 for *ER* were unavailable for some countries. Therefore, this work used the interpolation method to complete the data for a balanced panel. This work follows the [9,18] to take patents related to environmental technologies as a proxy for *ER*. The data for *ER* and *EF* were retrieved from OECD and GFN respectively. Renewable energy data were obtained from the World Bank. RE consists of solar, wind, and hydropower energy. Democratic accountability data has been obtained from the ICRG database. ICRG index consists of a range from 0 to 6. The high value represents more democratic accountability and vice versa. Globalization data were obtained from the KOF institute. The data for economic growth were obtained from the world bank.

### 3.1. Methodology

This work relies on panel data estimation because the data are for 29 years with 11 cross sections. Before the econometric methods, it is compulsory to conduct cross sectional dependence (*CD*) test. Globalization has made all the countries on a single platform experience economic growth. Therefore, the data for the panel countries may have similar variations. This outcome can affect the consistency of the estimation method. To overcome this problem, Pesaran [43] is applied to *CD* in the panel data.

Therefore, the equation for this test is as follows:

$$CD = \sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i=1}^{n-1}\sum_{j=i+1}^{n}\partial_{ij}^{t}\right) \tag{3}$$

where $T$ and $N$ represent time and cross-sections. $\partial_{ij}^{t}$ is an association of errors. The next step is to check the slope homogeneity of the data. The nature of the panel data was introduced by Pesaran and Yamagata [44]. The equation form of slope test is as under:

$$\tilde{\Delta} = \sqrt{N}\left(\frac{N^{-1}\tilde{S} - K}{\sqrt{2K}}\right) \tag{4}$$

$$\tilde{\Delta}_{\text{adj}} = \sqrt{N}\left(\frac{N^{-1}\tilde{S} - E\left(\tilde{Z}_{iT}\right)}{\sqrt{var(\tilde{Z}_{iT})}}\right) \tag{5}$$

After examining the *CD*, the next step is to check the stationarity property of the data. The existence of *CD* can affect the results of first-generation unit root tests. Therefore, this work applies the second-generation unit root test of cross-sectionally augmented IPS (CIPS) and CADF tests. These tests control the *CD* in the data and provide robust results.

### 3.2. Co-Integration Test

This work moves forward to ascertain the co-integration among ecological footprints, RE, financial globalization, GDP, and natural resources. For this purpose, the work applies Westerlund [45] the cointegration test. The test is effective in providing robust results in the presence of *CD* in the data. The equations are as follows:

$$G_t = \frac{1}{N}\sum_{i=1}^{N}\frac{\partial_i'}{SE\partial_i'} \tag{6}$$

$$G_a = \frac{1}{N}\sum_{i=1}^{N}\frac{T\partial_i'}{\partial_i'(1)} \tag{7}$$

$$P_t = \frac{\partial'}{SE(\partial')} \tag{8}$$

$$\partial' = \frac{P_a}{T} \tag{9}$$

$\partial' = \frac{P_a}{T}$ shows the yearly correction.

### 3.3. Long and Short-Run Analysis

Among the available empirical methods of FMOLS and DOLS, this research selects the CS-ARDL method by Chudik et al. [46] to gain short and long-run coefficient values. CS-ARDL provides authentic results while considering the CD in the data. First-generation tests cannot do this. Therefore, the equation for this test is as under:

$$\Delta EF_{i,t} = \emptyset_i + \sum_{I=0}^{p_w} \emptyset_{ij} \Delta EF_{i,t-1} + \sum_{I=0}^{p_z} \emptyset_{ij} \, AEV_{i,t-I} + \sum_{I=0}^{p_z} \emptyset_{ij} \, Z_{i,t-I} + \varepsilon_{i,t} \tag{10}$$

where $Z_i$ = ($\Delta EF_t$ $AEV_t$) signifies the averages of cross-section and *AEV* shows a set of illustrative variables.

### 3.4. Robustness Check Test

To cross-check the findings and to ensure robustness, this work employs the augmented mean group (AMG) methods and fully modified ordinary least square (FMOLS). This method takes into account the CD and heterogeneity problems [47].

## 4. Results and Discussion

This section consists of all the test results in ascending form. This means the tests of CD, slope homogeneity test, unit root test, co-integration test, log run and short run analysis, and robustness check tests. Before the estimation, this work checks for any multicollinearity in the panel data. For this purpose, the variance inflation factor (VIF) is sought. Table 2 shows the relevant findings. It was noted that the value is below 5 for each variable. This means that there is no multicollinearity in the panel data.

**Table 2.** Variance inflation factor.

| Variable | VIF | 1/vif |
|---|---|---|
| lnRE | 3.45 | 0.289 |
| lnGLO | 2.07 | 0.482 |
| lnGDP | 1.96 | 0.511 |
| lnDEM | 1.21 | 0.829 |
| lnER | 1.03 | 0.974 |
| Mean VIF | 1.94 | |

The next step is to apply the CD test to check the cross-sectional dependence among the panel data. Table 3 is shows the results of the cross-sectional dependence analysis.

**Table 3.** Results of Cross-sectional dependence analysis.

| Variable | Test Statistics | *p*-Value | Mean abs ($\rho$) |
|---|---|---|---|
| lnEF | 26.787 *** | 0.000 | 0.74 |
| lnRE | 25.416 *** | 0.000 | 0.70 |
| lnGLO | 33.888 *** | 0.000 | 0.94 |
| lnGDP | 33.953 *** | 0.000 | 0.94 |
| lnDEM | −1.061 | 0.000 | 0.37 |
| lnER | 5.73*** | 0.000 | 0.25 |

Note: *** explains the level of significance at 1%.

It can be noted that data for *EF*, *ER*, *G*, *GL*, and *RE* present cross-sectional dependence at a 1% level except DEM. This means that the panel data of N-11 countries are interlinked strongly. This CD is due to similar socio-economic conditions. The next step is to check the slope homogeneity. Table 4 shows the relevant results.

**Table 4.** Slope Test.

| | Value | $p$ Value |
|---|---|---|
| $\widetilde{\Delta}$ | 13.553 *** | 0.00 |
| $\widetilde{\Delta}_{adjusted}$ | 15.560 *** | 0.00 |

Note: *** explains the level of significance at 1%.

According to Table 4, the delta and adjusted delta values are significant at a 1% level. The successive step is to find out the unit root test in the panel data. This work utilizes two-unit root tests of CIPS and CADF and Table 5 shows the relevant results.

**Table 5.** Unit root test.

| Variables | CADF | | CIPS | |
|---|---|---|---|---|
| | At Level | 1st Difference | At Level | 1st Difference |
| lnEF | −1.519 | −3.479 *** | −2.009 | −5.370 *** |
| lnRE | −1.512 | −3.488 *** | −1.794 | −4.866 *** |
| lnGLO | −1.721 | −3.777 *** | −2.180 | −4.674 *** |
| lnGDP | −1.894 | −2.374 ** | −1.590 | −3.438 *** |
| lnDEM | −2.512 *** | −3.301 *** | −2.036 | −4.826 *** |
| lnER | −3.217 *** | −5.150 *** | −4.454 *** | −5.793 *** |

Note: ***& ** explain the level of significance at 1%, and 10% respectively.

Unit root test findings are showing that all the variables have mix order of integration, but all the variables show stationarity at first difference. This means that ecological footprints, renewable energy, globalization, economic growth, democracy, and environmental regulations are moving together in the long run. The next step is to find out the co-integration in the panel data. For this purpose, Westerlund [45] is applied. Table 6 shows the relevant findings.

**Table 6.** Westerlund test.

| Stat | Value | Z Value | Robust $p$-Value |
|---|---|---|---|
| $G_t$ | −2.624 ** | −1.321 | 0.043 |
| $G_a$ | −10.496 ** | 0.506 | 0.030 |
| $P_t$ | −8.325 * | −1.943 | 0.067 |
| $P_a$ | −10.406 ** | −0.944 | 0.033 |

Note: ** and * explain the level of significance at 5% and 10% respectively.

According to the results, two values of the group and two values of the panel are significant at a 5%, and 10% level. This means that EF, RE, DEM, ER, GLO, and GDP are strongly co-integrated in the long run. This outcome further makes way to conduct cross sectional autoregressive distributed lag (CS-ARDL) approach to find out the coefficient values in the long and short run. CS-ARDL is an efficient approach that provides long and short run coefficient values for panel data. This methiod also provides error correction term (ECT). ECT provides the stability of the model. Short run values may differ from long run values. Table 7 is showing the results of the CS-ARDL method. The CS-ARDL method controls the CD in the panel data and provides short and long run values.

Table 7. CS-ARDL results.

| Short Run | Coef. | Std. Err. | Z-Value | *p*-Value |
|---|---|---|---|---|
| ΔlnRE | −0.148 * | 0.076 | −1.940 | 0.052 |
| ΔlnGLO | −0.182 ** | 0.076 | −2.390 | 0.017 |
| ΔlnGDP | 0.371 *** | 0.134 | 2.760 | 0.006 |
| ΔlnDEM | −0.066 ** | 0.032 | −2.050 | 0.041 |
| ΔlnER | −0.007 *** | 0.003 | −2.870 | 0.004 |
| Long Run Est. | | | | |
| lnRE | −0.093 ** | 0.044 | −2.090 | 0.036 |
| lnGLO | −0.100 ** | 0.040 | −2.500 | 0.012 |
| lnGDP | 0.211 *** | 0.080 | 2.650 | 0.008 |
| lnDEM | −0.038 ** | 0.018 | −2.160 | 0.031 |
| lnER | −0.004 *** | 0.001 | −2.940 | 0.003 |
| ECM | −0.762 *** | 0.112 | −6.810 | 0.000 |

***, **, and * explain the level of significance at 1%, 5%, and 10%, respectively.

The results are showing that economic growth is positively linked with EF. This result is similar to the findings of Zafar et al. [8] in G-7 nations. Economic growth is achieved with services and the consumption of goods. When the income level rises, it is accompanied by the consumption of food, energy, and water. It also generates waste at the industrial, transportation, and residential levels. Due to such consumption, the environment degrades, and EF enhances. This result is in line with the findings of Ahmed et al. [48]. The coefficient value of RE is −0.093. This means that a 1% increase in renewable energy is lowering EF by 0.093% in the long run. This result is similar to the findings of Nathaniel et al. [49] in CIVET nations, Peng et al. [50] for BRICS countries, as well as Ahmad et al. [17] for emerging countries. Energy use is essential for continued economic growth, and it is the renewable energy from solar, wind, and hydro power that enhances sustainable growth. Therefore, RE consumption can boost environmental quality with sound economic growth.

The value of environmental regulation is negative and significant. This means that a 1% increase in ER will lower the EF by 0.007% and 0.004% in the short run and long run in N-11 countries. This novel finding contradicts the findings of Omojolaibi et al. [1], who found that ER does not affect EF in MENA countries. Our finding is in line with the findings of Murshed et al. [9], who found that ER is improving the climate in South Asian countries. This result is showing that strict environmental regulations have the ability to lower the EF in N-11 countries. Environmental regulations lower the use of fossil fuels and enhance the usage of RE. ER is calculated by the patents-related environmental technologies. These technologies enhance the environmental related machineries that lower EF. Hence, N-11 countries should enhance environmental-related technologies to mitigate the EF.

Democracy is decreasing the ecological footprints. A 1% increase in democratic accountability is lowering EF by 0.066% in the short run and 0.038% in the long run in N-11 countries. This result is acutely consistent with the findings of Akalin et al. [15] in OECD nations but contradictory with the findings of Usman et al. [51], who documented that democracy increases the people's welfare only by increasing economic growth. Economic growth uses energy, which degrades the climate. This outcome is supporting the argument that democracy increases the freedom of speech through media and it also increases public awareness about environmental problems. This awareness further pressurizes the governments for strict environmental regulations [13]. Moreover, a high level of accountability and public participation are important components of democracy [14]. This kind of condition further makes it easy for government organizations to launch environmental policies and implement them at commercial and domestic levels. This finding is in line with the findings of Güngör et al. [14] and Acheampong et al. [52].

Finally, globalization is lowering EF in N-11 countries, indicating that globalization is supporting environmental sustainability in N-11 countries. This result supports the results of Ahmed and Le [41] in ASEAN nations but contradicts the findings of Ahmad et al. [53], who found that globalization escalates the ecological footprints in emerging countries. This finding is important for the N-11 countries. These countries should continue to import green technologies from the developed nations because it is helping to lower EF in the long run.

Table 8 shows the results of the robustness check analysis of AMG and FMOLS tests. AMG and FMOLS are efficient methods that can consider the cross-sectional dependence in the panel data while giving the authentic results. These methods provide results on the base of probability values. The findings endorse the results of the CS-ARDL method that ER, DEM, GLO, and RE are environmentally friendly but economic growth is contaminating the climate. This means that N-11 nations are still consuming high ratio of fossil fuels to achieve rapid economic growth. Therefore, it is need of the hour to increase the % of RE in total energy mix. Moreover, strict environmental regulations will encourage the corporate sectors to adopt RE. A graphical representation of the results is provided in Figure 2.

**Table 8.** Robustness check.

| | **AMG** | | **FMOLS** | |
|---|---|---|---|---|
| **Variable** | **Coefficient** | ***p*-value** | **Coefficient** | ***p*-value** |
| lnRE | −0.198 ** | 0.013 | −0.123 *** | 0.000 |
| lnGLO | −0.229 ** | 0.060 | −0.704 *** | 0.000 |
| lnGDP | 0.415 *** | 0.000 | 0.409 *** | 0.000 |
| lnDEM | −0.025 *** | 0.002 | −0.062 *** | 0.000 |
| lnER | −0.002 *** | 0.000 | −0.006 ** | 0.022 |

Note: ***, and ** explains the level of significance at 1%, and 5%, respectively.

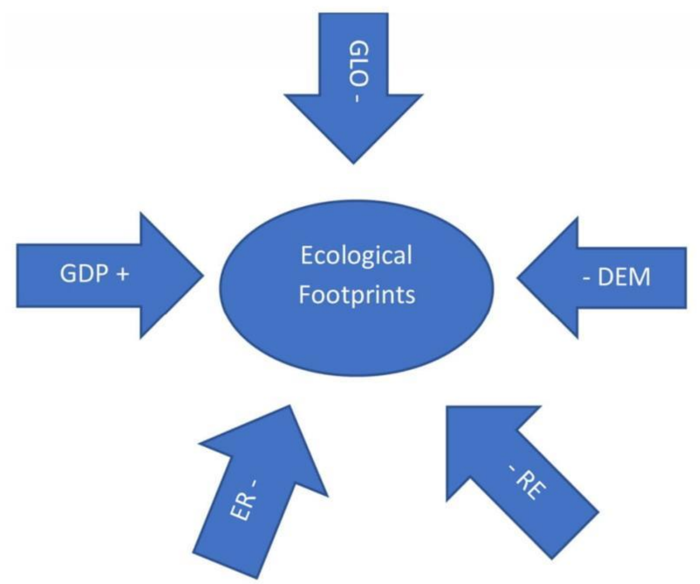


**Figure 2.** Graphical representation of results.

## 5. Conclusions and Policy Recommendation

This work probes the impacts of environmental regulations and democracy on ecological footprints in N-11 countries. Other important factors of economic growth, renewable energy, and globalization are also included in the model. This study utilizes the annual data from 1990–2018 and applies the second-generation unit root and cointegration tests of CIPS, CADF, and Westerlund. This work applies CS-ARDL with some robustness check tests, namely FMOLS and AMG tests. The findings show that democracy, environmental regulations, renewable energy, and globalization are contributing factors to environmental quality. Economic growth is increasing ecological footprints in N-11 countries.

Based on the findings, this work is suggesting that N-11 countries should strengthen their democratic institutions to mitigate their ecological footprints. Democratic accountability will strengthen the environmental regulations that increase renewable energy consumption. In this regard, it is important to enhance public participation in the environmental regulatory processes. The accountability for the allocation of investment for environmental-related purposes should also be increased. Media channels should be used to enhance public awareness about environmental problems. This aspect can be amplified by using the freedom of speech aspect of democracy.

Although N-11 countries have made many commitments to environmental sustainability, they have still heavily invested in fossil fuel-related energy. Therefore, high taxes should be imposed on fossil fuels to promote renewable energy. There is a need to invest in creating more environmental-related technologies. The role of globalization is vital in this regard because globalization has three dimensions of economic, political, and social globalization. These three indices play a fundamental role in increasing collaborative efforts of the people across the world. These collaborations further guide the developing nations in how to change their lifestyle according to a changing nature. Moreover, globalization helps to import environmentally friendly machinery from the developed world.

This work provides important insights regarding the impacts of democracy and environmental regulations on ecological footprints in N-11 countries. This study used a limited time dimension (1990–2018) for empirical analysis. Future research work can check the moderating role of environmental regulation in the nexus between economic growth and ecological footprint by expanding the time framework.

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## Appendix 2: Exploring the Estimation Effects of Structural Changes and Technology Innovations on Carbon Emissions

This a second article written in collaboration with international partners as part of my doctoral journey in contributing to the energy mix and nexus on exploring the estimation effects of structural changes and technology innovations on carbon emissions due to environmental degradation.

*sustainability*

MDPI

*Article*

# Estimating the Effects of Economic Complexity and Technological Innovations on $CO_2$ Emissions: Policy Instruments for N-11 Countries

**Jiangling Yu [1], Feng Ju [2], Muhammad Wahab [3], Ephraim Bonah Agyekum [4], Clement Matasane [5] and Solomon Eghosa Uhunamure [6,*]**

1 MBA Education Center, School of Management, Shandong University of Technology, Zibo 255000, China
2 School of Business Management, Weifang Vocational College, Weifang 261000, China
3 Department of Computer Science, The Government College University, Faisalabad 38000, Pakistan
4 Department of Nuclear and Renewable Energy, Ural Federal University Named after the First President of Russia Boris Yeltsin, 19 Mira Street, 620002 Ekaterinburg, Russia
5 Faculty of Engineering and Built Environment, Cape Peninsula University of Technology, P.O. Box 652, Cape Town 8000, South Africa
6 Faculty of Applied Sciences, Cape Peninsula University of Technology, P.O. Box 652, Cape Town 8000, South Africa
* Correspondence: uhunamures@cput.ac.za

**Abstract:** Every year, the problem of environmental degradation becomes more severe globally. It is widely believed that technological innovation and economic complexity are understood as structural transformations toward a more sophisticated and knowledge-based means of production as a viable way to fight against climate change. However, the studies integrating these two elements into the same environmental policy framework are still scant. With this in view, this study investigates the dynamic linkage between economic complexity, technological innovations, economic growth, and nonrenewable energy on $CO_2$ emissions in the N-11 nations. This study uses data from 1980 to 2020. It applies the recent method of cross-sectional autoregressive distributed lags (CS-ARDL). The cointegration method shows a strong association among the variables. The findings of the CS-ARDL show that technological innovations are negatively related to environmental degradation, while nonrenewable energy deteriorates the environment by escalating $CO_2$ emissions. This study fails to validate the EKC in the N-11 nations. In addition, economic complexity is helping these economies to achieve environmental sustainability by lowering environmental pollution. Based on the findings, this work recommends that the N-11 countries restructure their industrial sectors with low-carbon energy sources. For this purpose, these countries should increase their research and development budgets. This will help in launching environmentally friendly energy sources in their economic development model.

**Keywords:** economic complexity; $CO_2$ emissions; technological innovations; economic growth; N-11 nations

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## 1. Introduction

World economies are expanding their economic setup by using and preserving natural resources. In achieving economic stability, climate change has been considered a hurdle [1–3]. Higher industrial output further degrades the ecological atmosphere, which is unsuitable for achieving sustainable development goals (SDGs). The Next Eleven (N-11) countries are in transition mode and are aiming to increase their exports with more trade partners. For economic sustenance, these countries need to use energy sources of coal, gas, and oil [4,5]. As a result of these economic activities, the emissions of greenhouse gasses (GHGs) take place, which deteriorates environmental quality. Climate change is a global problem, and nations strive to mitigate the negative impacts through various agreements and treaties.

Today, the world's economies are enhancing their external relations to boost economic growth. These activities are increasing energy consumption and degrading the environment. The economic complexity (EC) index measures the export structure of an economy. The technology and knowledge in the manufacturing sector are the basic definitions of the EC. In other words, EC measures the knowledge and technology in a country's exports [6,7]. Hence, various degrees of EC show the intricacy and diversity of different nations [8]. This diversity of EC in different countries can affect the environmental quality in two ways; for more production and manufacturing, the countries need to explore and utilize more natural resources and energy. In this situation, the dependence on fossil fuels can be reduced for sustainable development [9]. Conversely, EC may stimulate business and research and development (R&D) and increase efficiency and competitiveness. These changes further bring structural changes and make ways for sustainable development. R&D stimulates economic growth through technological advancements for society and brings clean technologies [10]. Therefore, EC brings environmentally friendly technologies and provides sustainable energy in the economic sectors [11,12].

The Next Eleven (N-11) countries consist of 11 emerging nations. Rapid population and economic growth have increased the energy consumption of these countries. As a result, these countries have tried to lower energy costs and restructure their energy systems (IEA). The N-11 countries are at a junction for their future energy usage because these governments are calling for a reduction in the use of imported gas by increasing renewable energy. Currently, the N-11 countries are facing an elevated level of environmental pollution. Figure 1 shows the trend of $CO_2$ emissions from 1980 to 2020. Carbon emissions have been increasing for over three decades in the N-11 countries [13]. To attain the Paris Agreement's set target, these countries need to define their emission-reduction target. Currently, these countries are degrading their environmental quality through their energy sources and use. It shows that these countries still need to critically examine the climatic targets set in the Paris Agreement. Thus, emissions will continue to rise unless these countries take adequate measures. Despite the low cost of renewable energy, these countries significantly consume and depend on nonrenewable energy sources contributing to the carbon emission ratio. Figure 2 indicates the carbon emissions in units of million tonnes from these countries [13].

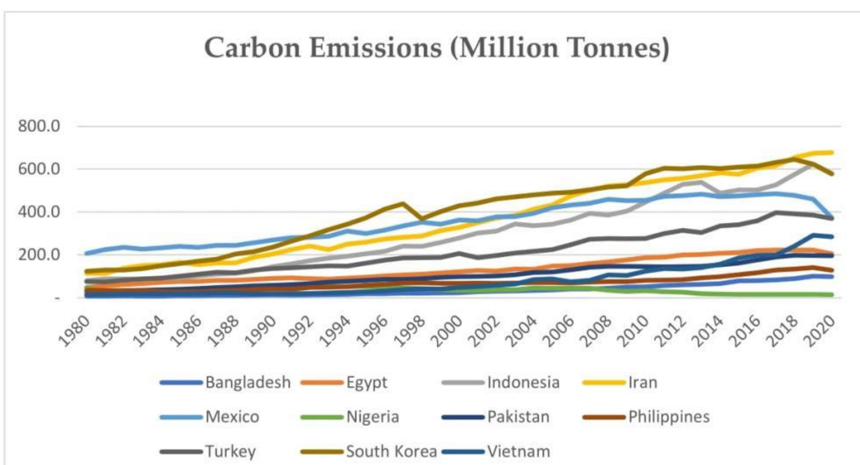


**Figure 1.** Trends of $CO_2$ emissions in the Next Eleven countries.

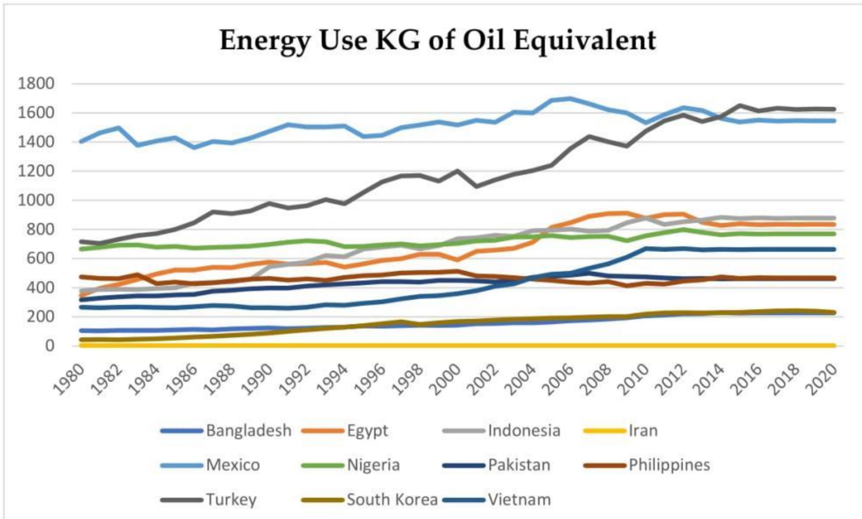


**Figure 2.** Trends of nonrenewable energy use in N-11 countries.

The literature has presented three possible theoretical justifications for the Gross Domestic Product (GDP) contamination association. Firstly, it is measured on the revenue flexibility for air quality. Secondly, it is associated with increased profits from efficient technologies, and thirdly, it is associated with economic activity based on economic complexity [14].

Along with the economic complexity of the service sector, policymakers and scholars have identified that innovations are the key factor in economic prosperity. Moreover, efficient technologies can be used against environmental problems around the world. According to endogenous growth, a country's economic development is ensured by the internal forces of human capital. Human capital increases economic growth through efficient technologies in the production process [15]. Technological advancements are due to economic motivations, which can be affected by the performance of the public and private sectors. Therefore, technological innovations are necessary to protect environmental resources as well as the promotion of economic expansion. This economic expansion further helps to develop and install modern technologies. Innovative technologies can reach marketplaces by diffusion, innovation, and invention [16].

Even though several studies have been conducted to explore the connection between environment and income, various spaces still need to be explored and can be solved. Therefore, this work investigates the impacts of technological innovations and economic complexity on $CO_2$ emissions in the N-11 countries. This work highlights the importance of the endogenous theory by presenting technological innovations as an endogenous factor. The study also assesses the roles of innovations and economic complexity in environmental degradation in the N-11 countries.

Economic complexity is vital for developing nations because it moves from agricultural economies toward industrial-based and information-based economies. Substantial movements in international trade, resource use, production process, and social and economic conditions are considered economic complexity [17]. This condition requires technological advancements because transitioning from fossil fuels to renewable energy requires some innovations. As a result, following the works of Adebayo et al. [17] and Ali et al. [18], this work takes economic complexity and technological advancements as determinants of environmental pollution in the N-11 nations.

Because of the importance of patent applications and industrial value added to environmental quality, this research work differs from past studies in the context of the N-11 nations. Additionally, this work adds to the literature by taking the value to add the industrial sector as a measure of economic complexity in the N-11 countries. Moreover, this work also investigates the environmental Kuznets curve (EKC) theory in the N-11 nations. The short- and long-run associations among the variables are determined by the cross-sectional autoregressive distributed lag (CS-ARDL) approach.

The structure of this article is as follows: the next section provides the literature review; the third section consists of data description, theoretical foundation, model, and methodology; the fourth section presents the results and discussion. The last section provides the conclusion and the policy implications of the study.

## 2. Literature Review

### *2.1. Carbon Emissions and Economic Growth*

Several studies are available in the literature that examined the association between GDP and $CO_2$ emissions. For example, Awosusi et al. [19] utilized the annual data for 1990–2018 and applied quantile regression. The study found that economic growth degrades the environment in the panel of NIC nations. The study validated the EKC. Adebayo et al. [20] found the same findings for Turkey that economic growth is not environmentally friendly. Akadiri et al. [21] applied the same technique to the data of 1990–2019 from the BRICS countries and found that economic growth increases $CO_2$ emissions. He et al. [22] analyzed the 1990–2018 data for ten energy transition economies and found that economic growth degrades the environmental quality. Xu [23] conducted a study for Brazil and took the load capacity factor as a proxy for environmental quality. The data analysis from 1970–2017 showed that GDP drives air pollution in Columbia. For Indonesia, Ahmed et al. [24] conducted a study by analysis of the data from 1971–2014. The study also found that environmental degradation is due to economic growth. However, contrarily, some research found that economic growth can be a tool to deal with $CO_2$ emissions. For example, the study by Usman et al. [25] showed that a 1% increase in GDP lowers $CO_2$ emissions. The study of Rjoub et al. [26] estimated the data from 1970–2018 in Sweden and found that economic growth decreases $CO_2$ emissions. Other studies also found that economic growth contaminates environmental quality [1,27–32].

### *2.2. Carbon Emissions and Innovations*

Technological advancement is considered to be a crucial factor contributing to a nation's economic progress. The research by Schumpeter [16] proved the theoretical background that technological advancement can reach the market in three ways, namely, diffusion, innovation, and invention. The scholar believed that research and development (R&D) could create the pathway for invention and innovation in any society. The execution and acceptance of a particular innovation can be described as diffusion. Therefore, these three variables contribute positively to the environment and the economy. Endogenous growth theory considers technological innovations to be a function of growth. Inconsistent results have been published by studies that calculate the impacts of innovations on $CO_2$ emissions. For example, the work of Kihombo et al. [33] studied the impact of innovations on carbon emissions over the years of 1990–2018. The results indicated that innovations have been mitigating carbon emissions over the years. For a global panel data set of 1990–2018, Kirikkaleli et al. [2] analyzed the impact of technological innovations on $CO_2$ emissions. The study found a positive role in abating carbon emissions. The study by Chen and Lee [15] investigated a panel of 96 countries and found that technological innovations are environmentally friendly. Similarly, the work of Khan et al. [34] analyzed the quarterly data from 2005Q1 to 2018Q4 and found that technological innovations mitigate $CO_2$ emissions. Gyamfi et al. [35], also found that technological innovations are lowering $CO_2$ emissions in Portugal. Adebayo et al. [36] found that technological innovations are increasing $CO_2$ emissions in Japan.

### 2.3. Carbon Emissions and Nonrenewable Energy Consumption

Energy is essential for economic growth, but its negligent use can create havoc on the environment. Nonrenewable sources of coal, oil, and gas are the foremost contributors to environmental degradation and pollution. Therefore, energy should be used responsibly. Several studies have found that the reckless use of energy can harm environmental quality [19,37]. Hanif et al. [38] showed that fossil fuel consumption degrades the environment. A study by Lotfalipour et al. [39] analyzed the annual data from 1967–2007 by applying ARDL and found that fossil fuels are lowering environmental quality in Iran. Dogan and Seker [40] analyzed the panel data of European countries and found that nonrenewable energy is contaminating the environment. Khan et al. [34] analyzed the panel data of 1990–2015 of OECD nations. The study indicated that nonrenewable energy is degrading the environment. Similarly, the work of Wada et al. [41] analyzed the data from 1971–2016 in Brazil and found that fossil fuels are degrading the environment.

### 2.4. Carbon Emissions and Economic Complexity

Economic complexity means transitioning from an agricultural-based economy to an industrial, production economy where more complex goods are produced, and this index has recently been added to the environmental literature. Economic complexity can play a crucial role in lowering environmental pollution in several ways. Most countries are moving from energy-intensive secondary industries toward service-based economies. A shift in an economy can be measured by its transition from an industrial-based economy toward a service-based economy. Even though there are many factors that measure the structure of an economy, these factors benefit from the developments in an economy. The economic complexity in any economy allows for an increase in industrial production, which then allows it to move toward a service-based economy. Agriculturally based and then industrial economies produce environmental pollution but shifting toward service-based businesses can help to mitigate environmental pollution. Therefore, changes in an economy's structure and its institutional framework help lower environmental pollution.

According to Kaufmann et al. [42], each country's manufacturing and EC require more natural resources linked to climate. Very few studies have probed the impact of EC on environmental quality. Doğan et al. [43] found that EC degrades the environment in low- and middle-income countries. High-income countries have a cleaner environment due to EC. Boleti et al. [44] investigated the data of 88 nations and found that EC enhances the environmental quality of the nations under investigation. Neagu et al. [45] found a long-run connection between energy use, environmental degradation, and EC in European nations. Other studies also found the detrimental role of EC on the environment in the G-7 nations [46–48]. There was also some disparity, demonstrated by the fact that EC sometimes improves environmental quality [49–51]. Chu [52] pointed out that EC degrades the environment, but stable institutional quality can control this impact.

Based on the mentioned studies, it is evident that there are mixed findings on the associations of economic complexity, economic growth, innovations, and nonrenewable energy. These inconsistent findings show the importance of further research for other countries. Moreover, this article applies the CS-ARDL method to find out the short- and long-run coefficient values for effective policymaking in the N-11 countries.

## 3. Data, Theoretical Foundation, Model, and Method

### 3.1. Data

This research analyzes the factors of environmental degradation via the proxy of $CO_2$ emissions. The factors of $CO_2$ emissions are economic growth (GDP), technological innovations (TI), nonrenewable energy (NRE), and economic complexity (EC). The annual data from 1980–2020 were analyzed (40 observations). Nonrenewable energy is included in the model to avoid the problem of omitted variables. The log form of all the data was checked for consistent results [4]. Table 1 shows the description and source of data taken for empirical analysis.

Table 1. Data description and their sources.

| Parameters | Symbol | Unit | Source |
|---|---|---|---|
| **Carbon Emissions** | $CO_2$ | Million tons | BP [53] |
| **Technological Innovations** | TI | Number of patents (resident + nonresident) | WDI |
| **Gross Domestic Product** | GDP | Constant USD | WDI |
| **Economic Complexity** | EC | Average complexity of the products (exports) | Economic complexity index |
| **Nonrenewable Energy** | NRE | KG of oil-equivalent per capita | WDI |

### 3.2. Theoretical Foundation

Romer's endogenous growth model and the production function were applied, and it is stated as follows:

$$Y = f\ (TI, J, K) \tag{1}$$

where Y shows income, and the output consists of technological progress, shown by (TI); J and K are the country's capital stock. Technological innovations measure technological progress (B). Economic growth has a distinct role in an economy, but it requires energy consumption, which creates greenhouse gases (GHGs) and contaminates the environment. Therefore, economic growth can be linked with environmental pollution ($CO_2$). The function of $CO_2$ will be as follows:

$$CO_2 = f\ (Y) \tag{2}$$

Since the factor of technology and capital define the output (economic growth), the function of $CO_2$ is as follows:

$$CO_2 = f\ (TI, K) \tag{3}$$

where, because a country's economic growth can impact $CO_2$ emissions, TI and K can influence $CO_2$ emissions. Capital can be classified into two categories: polluting and nonpolluting. The polluting capital will be from nonrenewable energy, and the nonpolluting capital will be from renewable energy. This is indicated in Equation (4).

$$K = K_e + K_{ne} \tag{4}$$

where $K_e$ denotes the degrading environmental capital; hence, the function of $CO_2$ will be as follows:

$$CO_2 = f\ (NRE, TI) \tag{5}$$

where nonrenewable energy use is represented by NRE. Economic activity can also be included in the model because production activities are for economic growth. The function can be written as follows:

$$CO_2 = f\ (NRE, TI, GDP) \tag{6}$$

It is suggested that when an economy moves from an agriculturally based economy to a manufacturing-based economy, it consumes more energy and degrades its environment. However, when a manufacturing-based economy moves toward a service-based economy, its energy consumption significantly lowers, and the environmental quality starts to improve. According to EKC, it is important to consider the economic complexity in an economy when measuring environmental quality. EC can be the best explainer of EKC. According to EKC, at the preindustrial level of an economy, income and pollution move together, but after reaching a threshold level (industrial production), pollution starts to decrease. This study follows the works of Ali et al. [18] and Ali et al. [53] for empirical analysis and model structuring. Therefore, the equation form of this work is as follows:

$$CO_2 = f\ (NRE, TI, GDP, EC) \tag{7}$$

In Equation (7), NRE, TI, GDP, EC, and $CO_2$ represent nonrenewable energy use, technological innovations, economic growth from [53], and economic complexity [54]. To check the validity of EKC, this includes the square form of GDP. Equation (8) is as follows:

$$CO_2 = f\ (\text{NRE, TI, GDP, EC, GDPs}) \tag{8}$$

Moreover, this work took the log form of the data to eliminate the problems of normality [55], and the log form equation is as follows:

$$lnCO_{2t} = \beta_0 + \beta_1\, lnNRE_{it} + \beta_2\, lnTI_{it} + \beta_3\, lnGDP_{it} + \beta_4\, lnEC_{it} + \beta_5\, lnGDPs_{it} + \epsilon_{it} \tag{9}$$

### 3.3. Cross-Sectional Dependence Test

The methodology starts with introducing the cross-sectional dependence (CD) test. A CD test informs one about any dependence among the countries of panel data. These test results further guide the econometric techniques for cointegration and long-run coefficient values. This work continues with the application of CD by Pesaran (2015) [55]. Therefore, the equation for this test is as follows:

$$CD = \sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i=1}^{n-1}\sum_{j=i+1}^{n}\partial_{ij}^{t}\right) \tag{10}$$

where $T$ and $N$ represent time and cross-sections. $\partial_{ij}^{t}$ is an association of errors.

### 3.4. Slope Homogeneity Test

The nature of the panel data was introduced by [56]. The equation for this test is:

$$\widetilde{\Delta} = \sqrt{N}\left(\frac{N^{-1}\widetilde{S} - K}{\sqrt{2K}}\right) \tag{11}$$

$$\widetilde{\Delta}_{\text{adj}} = \sqrt{N}\left(\frac{N^{-1}\widetilde{S} - E\left(\widetilde{Z}_{iT}\right)}{\sqrt{var\left(\widetilde{Z}_{iT}\right)}}\right) \tag{12}$$

### 3.5. Unit Root Test

If the existence of CD is validated among the data, then it is important to conduct second-generation unit root tests. For this purpose, cross-sectionally augmented IPS (CIPS) and cross-sectionally augmented DF unit root tests can be applied. These tests will determine the order of $CO_2$, NRE, TI, GDP, and SCH integration.

### 3.6. Cointegration Test

This work moved forward to investigate the cointegration among $CO_2$ emissions, nonrenewable energy, technological innovations, GDP, and economic complexity. For this purpose, the work applies [57]. The test effectively provides robust results in the presence of CD in the data. The equations for this test are as follows:

$$G_t = \frac{1}{N}\sum_{i=1}^{N}\frac{\partial_i^!}{SE\partial_i^!} \tag{13}$$

$$G_a = \frac{1}{N}\sum_{i=1}^{N}\frac{T\partial_i^!}{\partial_i^!(1)} \tag{14}$$

$$P_t = \frac{\partial^!}{SE(\partial^!)} \quad (15)$$

$$\partial^! = \frac{P_a}{T} \quad (16)$$

$\partial^! = \frac{P_a}{T}$ represents the ratio of correction, yearly.

*3.7. Short-Run and Long-Run Analysis*

Among the available econometric techniques of fully modified ordinary least squares (FMOLS) and dynamic ordinary least squares (DOLS), this research selects the CS-ARDL approach by Chudik and Pesaran [58] to gain short- and long-run coefficient values. CS-ARDL provides authentic results while considering the CD in the data. Therefore, this study has opted for a methodology that could address potential endogeneity issues. For instance, the CS-ARDL approach was applied, which is robust in the presence of misspecification bias, serial correlation of error terms, cross-sectional dependency, nonstationarity, and the endogeneity bias problem. First-generation tests cannot perform this. Therefore, the equation for this test is as follows:

$$\Delta EF_{i,t} = \varnothing_i + \sum_{I=0}^{p_w} \varnothing_{ij} \Delta EF_{i,t-1} + \sum_{I=0}^{p_z} \varnothing_{ij} AEV_{i,t-I} + \sum_{I=0}^{p_z} \varnothing_{ij} Z_{i,t-I} + \varepsilon_{i,t} \quad (17)$$

$Z_i$ = ($\Delta EF_t$ $AEV_t$) represents the cross-section averages, and AEV shows a set of explanatory variables.

*3.8. Robustness Check Test*

To cross-check the findings and ensure robustness, this work continues to apply the augmented mean group (AMG), FMOLS, and DOLS methods. This test is valid because it captures the heterogeneity and cross-section dependence problems [59].

## 4. Results and Discussion

This section consists of the results of the methods used for the analysis. For this purpose, the CD, slope homogeneity test, unit root tests, cointegration test, CS-ARDL test, and robustness check tests are presented sequentially. First, it is important to check for cross-sectional dependence in the panel data of the N-11 countries. Table 2 presents its findings.

**Table 2.** Results of cross-sectional dependence analysis.

| Variable | Test Statistics | Prob | Abs (corr) |
|---|---|---|---|
| $CO_2$ | 45.048 *** | 0.000 | 0.949 |
| TI | 31.372 *** | 0.000 | 0.661 |
| EC | 23.937 | 0.000 | 0.531 |
| GDP | 42.021 *** | 0.000 | 0.885 |
| NRE | 21.691 *** | 0.000 | 0.694 |

Note: *** explains the level of significance at 1%.

The panel data of carbon emissions, technological innovations, economic complexity, economic growth, and nonrenewable energy have cross-sectional dependence. This means that any shock in country variable will disturb the other countries' data. This CD may be due to the similar socio-economic policies of the N-11 nations. The next step is to check the slope homogeneity property of the data, and Table 3 shows its results.

**Table 3.** Slope test.

| | Value | p-Value |
|---|---|---|
| Delta | 25.499 *** | 0.000 |
| adj | 28.002 *** | 0.000 |

Note: *** explains the level of significance at 1%.

The p-value is significant. This means that panel data suffer from heterogeneity problems. Therefore, the second-generation unit root test is suitable for finding the panel data's unit root. For this purpose, this study applies two unit root tests, CIPS and CADF. Table 4 shows the findings.

**Table 4.** Unit root test.

| Variable | CIPS | | CADF | |
|---|---|---|---|---|
| | At Level | 1st Difference | At Level | 1st Difference |
| $CO_2$ | −1.670 | −5.169 *** | −2.041 | −3.648 *** |
| TI | −2.360 ** | −5.690 *** | −2.041 | −4.298 *** |
| EC | −1.578 | −5.194 *** | −1.860 | −4.256 *** |
| GDP | −2.456 *** | −4.286 *** | −2.187 ** | −3.228 *** |
| NRE | −2.328 ** | −5.565 *** | −2.245 ** | −4.114 *** |

Note: *** and ** explain the level of significance at 1% and 5%, respectively.

The panel data are integrated at first difference. This means that carbon emissions, technological innovations, economic complexity, economic growth, and nonrenewable energy are moving together in the long run. This outcome further encouraged this study to conduct the cointegration test. For this purpose, the Westerlund test was applied. This test is efficient in controlling the panel data. This test provides efficient results by considering the CD in the data. Table 5 shows its findings.

**Table 5.** Westerlund test.

| | $G_t$ | Ga | $P_t$ | Pa |
|---|---|---|---|---|
| Test statistics | −2.446 *** | −9.566 *** | −6.717 *** | −5.794 *** |
| Robust p-values | 0.000 | 0.000 | 0.000 | 0.000 |

Note: *** explain the level of significance at 1%.

Table 5 shows that the values of Ga, Pt, and Pa are significant at 1% and 5%. This outcome shows that the panel data of the N-11 countries are cointegrated strongly in the long run. Carbon emissions, technological innovations, economic growth, economic complexity, and nonrenewable energy are cointegrated in the long run. The CS-ARDL approach was applied to know the coefficient values of independent variables. The CS-ARDL approach provides short-run and long-run coefficient values. This test also provides the error correction term (ECT), which shows the stability of the model. Table 6 shows the findings of the CS-ARDL method.

**Table 6.** CS-ARDL.

| Short-Run | Coefficient | ST ERROR | Z-Value | PROB |
|---|---|---|---|---|
| $\Delta lnTI$ | −0.020 * | 0.010 | −1.92 | 0.054 |
| $\Delta lnEC$ | −0.068 *** | 0.021 | −3.21 | 0.000 |
| $\Delta lnGDP$ | −0.073 | 0.016 | −4.60 | 0.000 |
| $\Delta lnGDPs$ | 0.042 ** | 0.017 | 2.55 | 0.011 |
| $\Delta lnNRE$ | 0.612 *** | 0.154 | 3.96 | 0.000 |
| | | Long-run results | | |
| $lnTI$ | −0.012 ** | 0.006 | −1.97 | 0.048 |
| $lnEC$ | −0.038 *** | 0.011 | −3.34 | 0.000 |
| $lnGDP$ | −0.041 *** | 0.008 | −4.59 | 0.000 |
| $lnGDPs$ | 0.026 *** | 0.009 | 2.59 | 0.009 |
| $lnNRE$ | 0.355 *** | 0.093 | 3.82 | 0.000 |
| ECM | −0.691 *** | 0.056 | −12.44 | 0.000 |

***, ** and * explain the level of significance at 1%, 5 and 10%, respectively.

The results shows that economic growth is lowering the $CO_2$ emissions in the N-11 countries. This means that a 1% increase in GDP lowers $CO_2$ emissions by 3.06% in the long run. This outcome shows that the N-11 countries are on the right track and that their economic progress is environmentally friendly. This finding is different from the findings of Kirikkaleli et al. [5] and Adebayo et al. [20]. The N-11 countries are adopting sustainable energy policies, and economic growth significantly lowers the pollution burden. The value of the square of GDP is positive. This means that after reaching some threshold level, economic growth will degrade environmental quality. This means that the N-11 countries will compromise their environmental quality to achieve future economic growth. This finding is vital for policymakers to implement strict environmental regulations to keep the environment clean in the future. This result cannot validate the EKC in the N-11 nations. Moreover, this finding is different from the findings of Ali et al. [18].

The role of nonrenewable energy is negative for $CO_2$ emissions in the N-11 countries. This means that a 1% increase in energy use will raise $CO_2$ emissions by 0.93% and 0.50% in the short and long run. This finding correlates with the results of He et al. [22] and Pata and Isik [57]. This result is justifiable because the N-11 countries are in transition mode and are working toward becoming progressive countries. In this endeavor, these countries are using nonrenewable energy sources and degrading their environment [60].

The findings also confirm that technological innovations (TI) are lowering $CO_2$ emissions. This means that a 1% increase in innovations reduces 0.02% carbon emissions in the short and long run. Adebayo et al. [61] also found the findings that technological innovations improve energy efficiency and reduce energy intensity. As a result, TI improves the air quality. The N-11 countries are increasing their research and development to increase energy efficiency. Therefore, the number of patents in these countries rose rapidly. This work found the positive impact of EC on $CO_2$ emissions. This means that a 1% increase in economic complexity lowers $CO_2$ emissions by 0.068% and 0.038% in the short and long run. The observation of the international energy agency (IEA) that the tertiary sector is good for the environment is correct. Service-based economies mitigate $CO_2$ emissions. It becomes good when an economy moves from agricultural to industrial and then to a tertiary base. As income increases, people start to care about their environment. Economic structural revolution further encourages innovations because economic complexity has assisted these economies to mitigate climate change. Therefore, these countries are moving toward sustainability. These findings contradict the findings of Ali et al. [62], which revealed that economic complexity is degrading the environment in Pakistan. The robustness check is presented in Table 7.

**Table 7.** Robustness check.

| Variable | AMG | FMOLS |
|---|---|---|
| ***lnTI*** | −0.02 *** | −0.07 ** |
| ***lnEC*** | −0.03 ** | −0.09 *** |
| ***lnGDP*** | −0.59 *** | −1.61 *** |
| ***lnGDPs*** | 0.14 ** | 0.33 *** |
| ***lnNRE*** | 0.92 *** | 1.29 *** |

Note: ** and *** explain the level of significance at 5%, and 1%, respectively.

The robustness check results of AMG and FMOLS indicate similar findings to that of CS-ARDL.

*Causality Test*

After checking the robustness of the results, this work moved forward to learn the causal effect among the variables. For this purpose, the Dumitrescu Hurlin Panel causality test was applied. This test provides authentic results while considering the problems of panel data. Table 8 shows its findings.

**Table 8.** Causality Test.

| Null Hypothesis | W-Stat. | Prob. |
|---|---|---|
| EN → $CO_2$ | 2.30764 | 0.7985 |
| $CO_2$ → EN | 3.94754 *** | 0.0108 |
| GDP → $CO_2$ | 4.90798 *** | 0.0001 |
| $CO_2$ → GDP | 4.80766 *** | 0.0002 |
| GDP2 → $CO_2$ | 4.82822 *** | 0.0002 |
| $CO_2$ → GDP2 | 4.66154 *** | 0.0004 |
| EC → $CO_2$ | 5.73630 *** | $4 \times 10^{-7}$ |
| $CO_2$ → EC | 4.03640 *** | 0.0075 |
| TI → $CO_2$ | 3.16310 | 0.1468 |
| $CO_2$ → TI | 9.69363 *** | 0.0000 |
| GDP → EN | 4.41762 *** | 0.0014 |
| EN → GDP | 4.25887 *** | 0.0029 |
| GDP2 → EN | 4.39632 *** | 0.0015 |
| EN → GDP2 | 4.24143 *** | 0.0031 |
| EC → EN | 4.47578 *** | 0.0010 |
| EN → EC | 5.04872 *** | $4 \times 10^{-5}$ |
| TI → EN | 2.84707 | 0.3128 |
| EN → TI | 6.83893 *** | $4 \times 10^{-11}$ |
| GDP2 → GDP | 3.96788 *** | 0.0100 |
| GDP → GDP2 | 3.87206 *** | 0.0146 |
| EC → GDP | 2.98563 | 0.2290 |
| GDP → EC | 5.32711 *** | $8 \times 10^{-6}$ |
| TI → GDP | 3.04599 | 0.1980 |
| GDP → TI | 4.90728 *** | 0.0001 |
| EC → GDP2 | 2.86070 | 0.3038 |
| GDP2 → EC | 5.30554 *** | $9 \times 10^{-6}$ |
| TI → GDP2 | 3.07250 | 0.1853 |
| GDP2 → TI | 4.96537 *** | $7 \times 10^{-5}$ |
| TI → EC | 2.94875 | 0.2495 |
| EC → TI | 4.26908 *** | 0.0027 |

*** shows significance at 1% level.

There is a feedback causal association between GDP, carbon emissions, economic complexity, and energy use. Moreover, economic complexity and energy use are causing each other. One-directional impact goes from $CO_2$ to energy use, from $CO_2$ to technological advancements, from energy use to technological progress, from economic growth to economic complexity, from economic growth to technological progress, from industrial value to technological progress.

## 5. Conclusions and Policy Implications

This work investigates the impacts of economic complexity, technological innovations, nonrenewable energy use, and economic growth on $CO_2$ emissions in N-11 countries. For empirical analysis, this work adopts the second-generation methodologies. The annual data for 1980–2020 are analyzed and the findings confirm that economic growth is improving air quality in the short and long run, but its square term is degrading the environment. This outcome is crucial for the N-11 nations because the EKC was not validated. Moreover, technological advancement is environmentally friendly in these nations. During the research period of 1980–2020, the number of patents significantly increased in the N-11 nations.

Based on the findings, the following suggestions are recommended for the N-11 countries. These countries need to increase the number of patents because it will increase energy efficiency and reduce carbon emissions in the N-11 countries. As the N-11 nations are heading toward more economic growth, their investment should also be toward ecofriendly and innovative industry technologies. Economic complexity is environmentally friendly because $CO_2$ emissions can be lowered by increasing tertiary-sector processes. Therefore, this study suggests service-based growth for the Next Eleven countries. In this regard, it is recommended that service sector-based trade, service sector-based companies, and international collaborations to increase services should be enhanced in the N-11 nations. A service-based economy holds a basic position in any country because it enhances employment opportunities and wealth creation. Therefore, these countries should enhance service-based growth by creating public–private engagement. Policymakers should make national policies for service-based growth for sustainable development. In doing so, the current hurdles in regulations should be addressed to form a service-based economy.

The industries should not only be capital-intensive, but also green-intensive sectors. The findings also show that the industrial sector in the N-11 countries contaminates environmental quality. This may be because the N-11 nations need to restructure their energy resources in industries. The traditional energy resources are emitting greenhouse gases and creating environmental damage. These countries must launch renewable sources in industries on an emergency basis and should try to enhance the service-based sectors to boost economic growth. These countries have diverse backgrounds and almost the same environmental degradation rate. These countries have to increase their research and development budgets. Past research has documented that the shift from a manufacturing-based economy toward a service-based economy reduces energy consumption, which helps lower emissions of GHGs. At the same time, these countries must introduce renewable energy sources at domestic levels for a cleaner environment.

This research work enhances the literature by including the roles of economic complexity, economic growth, and technological innovations on $CO_2$ emissions for N-11 countries. Future research can include other factors of technological innovations and financial risk to present interesting findings for other groups of countries.

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**Appendix 3: The Data Validation and Permission from the South African Weather Services (SAWS).**

This section provides the data validation as authorised, and give by the authorized data centre, with the written permission from the South African Weather Services (SAWS).

South African Weather Service

ISO 9001 Certified Organisation

**DISCLOSURE STATEMENT**

The provision of the data is subject to the User providing the South African Weather Service (SAWS) with a detailed and complete disclosure, in writing and in line with the requirements of clauses 1.1 to 2.4 (below), of the purpose for which the specified data is to be used. The statement is to be attached to this document as Schedule 1.

1 **Should the User intend using the specified data for commercial gain then the disclosure should include the following**:

1.1 the commercial nature of the project/funded research project in connection with which the User intends to use the specified data;

1.2 the names and fields of expertise of any participants in the project/funded research project for which the specified data is intended; and

1.3 the projected commercial gains to the User as a result of the intended use of the specified data for the project/funded research project.

2 **Should the User intend using the specified data for the purposes of conducting research, then the disclosure should include the following**:

2.1 the title of the research paper or project for which the specified data is to be used;

2.2 the details of the institution and supervisory body or person(s) under the auspices of which the research is to be undertaken;

2.3 an undertaking to supply SAWS with a copy of the final results of the research in printed and/or electronic format; and

2.4 the assurance that no commercial gain will be received from the outcome from the research.

If the specified data is used in research with disclosure being provided in accordance with paragraph 2 and the User is given the opportunity to receive financial benefit from the research following the publication of the results, then additional disclosure in terms of paragraph 1 is required.

The condition of this disclosure statement is applicable to the purpose and data requirements of the transaction recorded in Schedule 1 on page 2. This statement is effective from June 2018.

Bolepi House, 442 Rigel Avenue South, Erasmusrand, 0181 Private Bag X097, Pretoria, 0001 Tel: + 27 (0) 12 367 6000

Weatherline: 083 123 0500 www.weathersa.co.za sms line: *120*555# (Dial)

## Disclosure Statement

SCHEDULE 1

**Please note**: The South African Weather Service will only act upon customer requirements noted on this disclosure statement and not from any other correspondence.

**FULL PERSONAL DETAILS OF USER**

| | |
|---|---|
| Full Names | Clement Matasane Matasane |
| University/school/organisation | Cape Peninsula University of Technology |
| Student Number (if applicable) | 194074129 |
| Email address | mmatasane@yahoo.com |
| Cellphone | 0787374299 |
| Supervisor | Prof MTE Kahn |
| Project/Thesis Title | Assessment of Renewable Energy Potentials in Vhembe District Municipality, Limpopo Province, South Africa Using GIS as a Decision Support System |
| Registered Degree (e.g. BSc ) | PhD |
| Expected finalization date (MMYYYY) | 2023 |

**THE PURPOSE** (*Please indicate a detailed description of the purpose for which the data will be used)*

Development of Solar Energy requires radiation dat to determine the actual and variations on the irradiance measurements for the specific areas. As this project involves the Vhembe District, the radiation varies with topology and area. The data required to estimate and make measurements for different areas and mathematical analysis to be used in the formulae develop for the different solar energy setups.

**DATA REQUIRED** *(Please include the weather elements (e.g. rain, temperature), place/s and time period)*

I would like to request for the weather elements (temperature radiation, humidity, wind, and rain) for the Vhembe District from June 2018 to July 2019.

I hereby accept that:

- SAWS will be acknowledged in the resulting thesis/project or when published, for the data it provided.
- SAWS will be provided with a copy of the final results in printed or electronic format.
- The data received shall not be provided to any third party.

Signature of the User: Date: 11 August 2018

(*Please sign the document and do not type your name in as this is a legal document and requires a signature*.