UNIVERSITY OF NAIROBI

LOCATION OF SUITABLE SITES FOR WIND FARMS IN LAIKIPIA COUNTY

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ABSTRACT

In Kenya, a wide gap exists between wind resource and actual energy production, and it is imperative to expand the wind energy development, being cleaner and climate-friendly. Because of the formidable costs associated with wind energy development, the locations for new wind turbines need to be carefully selected to provide the greatest benefit for a given investment. In this study, the adopted siting criteria were identified based on expert opinion and literature review, a relevant GIS database was created and a GIS-based multi-criteria approach developed to identify the areas that are best suited for wind energy development in Laikipia County, Kenya. The adopted multi-criteria approach utilizes AHP to determine weights of the siting criteria (factors and constraints) and develops a composite suitability map from single-factor maps representing these criteria.

The developed decision support tool is capable of identifying priority areas for wind farm development with the results of this work indicating approximately 3.24% of the total study area being of high suitability, 31.07% of medium suitability and 3.04% of low suitability. A follow up study can be conducted to find out the community response to any potential wind installation on their land, as the approach selected could help support sustainable spatial policy development on all levels of public administration related to renewable resources use.

DEDICATION

To my late Dad, Mzee Charles Mboya - You taught me Patience, hard work, Integrity, Love, Compassion and the values that are the guiding pillars of my Life. I also dedicate this project to Mrs Margaret Mboya who has taught me to strive for whatever it is that I want and to give my all in order to succeed. Mum, you motivated me to continue staying focused in school.

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LIST OF ABBREVIATIONS

AHP: Analytic Hierarchy Process

COP 21: 21st Conference of Parties

ERC: Energy Regulatory Commission

GIS: Geographic Information System

GOK: Government of Kenya

GW: gigawatt

IEA: International Energy Agency

IPP: Independent Power Producer

IRENA: International Renewable Energy Agency

KNBS: Kenya National Bureau of Statistics

LPG: Liquefied Petroleum Gas

MCDA: Multi-Criteria Decision Analysis

MCDM: Multi-Criteria Decision Making

MW: megawatt

NRC: National Research Council

NREL: National Renewable Energy Laboratory

UNEP: United Nations Environment Programme

UTM: Universal Transverse Mercator

WGS: World Geodetic System

1. INTRODUCTION

1.1 Background

Climate change has become a threat to our species. Its implications are negatively affecting global biodiversity, human health, food and water security, and even threatening our cultures. It has been argued that the variations in the global climate are normal and natural changes of the earth's system; however, the human contribution to such variations cannot be denied. The concentration of carbon dioxide in the atmosphere has exponentially increased since the late 1700s; the age of industrial revolution, that also brought intense energy requirements supplied now mostly by the endless burning of fossil fuels (NRC, 2010)

According to UNEP, anthropogenic Carbon dioxide emissions have increased four times faster since 2000, than in the previous decade. Most of the emissions come from burning of fossil fuels (UNEP, 2009). In Kenya, the energy generation mix comprises wood fuel, petroleum and electricity accounting for 69%, 22% and 9% of the total energy use respectively. More precisely, 67.5% of the electricity is generated using renewable energy sources, which are predominantly hydro with a 47.8%, geothermal with 12.4% and wind 0.3% shares respectively, while 32.5% of the electricity generated is from fossil fuels. Kenya’s electricity sub-sector is facing challenges of rapidly growing demand for electricity, high dependence on hydro-electric power and high costs of supply. Against these challenges, the government’s strategy for expanding infrastructure in the sector is to promote equitable access to quality energy services at the least cost while protecting the environment. Renewable energy development especially wind, is expected to play a role in overcoming the country’s power problems (Macro Planning Directorate, 2008).

Besides the environmental concerns, Kenya faces a threat associated with energy security. The hydro-led power experienced a production decline of 9% due to drought, since 2008. Although oil-fired power plants played an auxiliary role and increased the generation by 23% from 2007 to fill in the shortage of hydroelectric power, increasing dependence on imported oils may raise electricity prices and affect other economic activities negatively.

The geographical conditions of some parts of Kenya, give very good potential for the development of renewable wind energies (GOK through Ministry of Energy and Petroleum), having different areas with wind potential capacity of 1604GW (7.75-7.25 m/s), 642GW (7.25-6.50 m/s) and 4.6GW (6.5-6.0 m/s). Nevertheless, at present, the expansion of wind energy infrastructure concerns land-use planning, and thus involves economic profitability and nature conservation. In this sense, wind farms must provide a sufficient wind resource to be viable.

GIS is a computer-based system which is designed to store and process geographic information (Hansen, 2005), whereas MCDA can be described as a collection of techniques and procedures for structuring decision problems, and designing, evaluating and prioritizing alternative decisions (Malczewski, 2006). Since GIS has the ability to incorporate and analyze multiple spatially related criteria in a decision-making context, the combination of GIS and MCDA can be described as a process which transforms and combines geographical data and value judgments in order to obtain information for decision making (Malczewski, 2006). As such, by implementing a MCDA model within a GIS environment, a decision support tool aiming at evaluating wind farm site suitability could be generated.

1.2 Problem Statement

Like many African countries, Kenya has been primarily dependent on hydro and fossil fuels. With the country urbanizing faster than most regional countries, there is need to develop a decision support tool that will help identify the most suitable locations for alternative sources of renewable energy, especially wind energy, in a bid to insulate the country's power tariff by providing a low cost, environment friendly and consistent power source to cater for the increasing electricity demand in the country.

1.3 Objectives

a) Main Objective

The main objective of this study is to determine the most suitable sites for the location of wind farms in Laikipia County.

b) Specific Objectives

i. To identify the relevant criteria for location of suitable sites for wind farms in Laikipia county.
ii. To weight the criteria.

iii. To create a relevant GIS database

iv. To perform Multi-criteria analysis and identify the most suitable sites for location of wind farms in Laikipia County.

1.5 Organization of the Report

This report consists of five chapters. The chapters are briefly explained in the following:

1. **Introduction**: This chapter explains, in general, the background to the study followed by the significance of the study under the problem statement and objectives.

2. **Literature Review**: This Chapter discusses the challenges of inadequate energy Supply in Kenya as a Country, and further discusses the supply of energy in Kenya and Laikipia County. The chapter proceeds to give a general overview of the Concept of green energy, Wind farms and their locations and the MCDM Process. Some case studies that illustrate how GIS has been used in wind farm planning are also presented.

3. **Methodology**: This chapter explains the geographical location of the study area and also describes the contributing factors that influence the development of wind power in Laikipia County. The sources and methods of data collection are discussed together with the application of AHP as a Multi-criteria approach to determine the overall criteria weights. Further, the process of applying the Weighted Overlay method in GIS environment to identify the suitable and restricted site in study area is discussed.

4. **Results and Discussion**: This chapter presents the results of the modelling procedure along with discussion of the results.

5. **Conclusions and Recommendations**: This chapter concludes the study and also offers a list of recommendations to be considered by Laikipia County as the next steps toward promoting and assisting in the development of successful wind power projects Laikipia County.

These chapters are followed by a list of references and seven appendices

2. LITERATURE REVIEW

2.1 The Challenge of Inadequate Power Supply in Kenya

Energy supply has become a growing concern in Kenya and an important factor towards achieving growth and development. Future economic growth crucially depends on the long-term availability of energy from sources that are affordable, accessible, and environmentally friendly. However, the country is faced with serious energy supply problems including, over-reliance on hydropower; insufficient power generation capacity; insufficient focus on alternative energy sources; increasing high oil import bills; lack of investment in new power generation units; high transmission and distribution costs, transmission losses; poor power quality and reliability; insufficient focus on alternative energy sources; and lack of access to modern electricity for a large segment of the population (Owiro *et al*., 2015).

In addition, the country faces a widening gap between electricity demand and supply which is being exacerbated by urbanization, economic development, population growth and rural electrification. Electricity demand has been growing consistently at 7.9% per annum (Kairu, 2017). As a result, the existing system is greatly strained and the frequency of blackouts or brownouts is increasing, constraining industrial production and provision of socioeconomic services as well as deterring foreign investment.

Furthermore, inefficient production and unsustainable use of biomass energy in Kenya is contributing to environmental degradation, such as high deforestation, desertification, and soil erosion. The use of wood, charcoal and crop residues as fuel also results in indoor air pollution which causes severe human health impacts directly to the users, especially rural women. Moreover, the task of gathering traditional supplies of wood-fuel is time-consuming and exhausting. This burden is borne by women and children, who are then diverted from other activities such as education and farming that could eventually have improved their productivity and living conditions. Thus, improving the energy supply situation and, in particular, increasing access to electricity, are of prime concern in Kenya.

2.1.1 Energy Supply in Kenya

The primary energy supplies of the country consist of petroleum and electricity, with wood fuel providing the basic energy needs of the rural communities, urban poor, and the informal sector. An analysis of the national energy shows heavy dependence on wood fuel and other biomass that account for 68% of the total energy consumption (petroleum 22%, electricity 9%, others account for 1%) (Omenda and Simiyu, 2015).

100% of petroleum and petroleum products in Kenya are imported and the country spends about 140 billion Kenya Shillings per annum on the import of petroleum products (Kiplagat *et al*., 2011). However, economically exploitable oil deposits were discovered in North-Western Kenya in 2012, although the production of oil in this site has not started yet.

Electricity in Kenya is generated from Geothermal, Hydropower, Thermal, Bagasse Cogeneration and Wind accounting for 27.01%, 37.69%, 32.93%, 1.17% and 1.17% respectively. Kenya's current installed electricity capacity is estimated at 2.4 GW, 1.5 GW of which is grid-connected and 500 MW of which has come online since mid-2014 (ERC, 2015). Since Hydropower accounts for a large percentage of this capacity and is reliant on unpredictable weather conditions, the frequency of power outages is high at 33% (compared to 1% in Mexico, China, and South Africa).

The current overall electrification rate in Kenya is 55%, with 86.75% of the urban population and only 42.8% of the rural population having access to electricity, leaving almost 70% of the total population in Kenya living in rural areas, having access only to wood and paraffin as major energy resources. (Ford, 2017).

Whilst electricity generation in Kenya is still entirely operated by one state-owned company- KenGen Limited- the participation of IPPs is growing. There are approximately 10 IPPs in operation and they account for about 24% of the country's installed capacity, up from 11% in 2008. However, there are concerns about the low efficiency of the power production by the IPPs. Kenya also Imports electricity from Uganda and Ethiopia. Power from Ethiopia is not connected to the Kenyan National Grid, and only serves the border town of Moyale.

Table 1 presents the sources of electricity as at 2015. Hydropower remains the primary electricity source and accounts for 37.69% of the total electricity supply for the country.

Table 1: Installed effective electricity Capacity in Kenya as at 2015

Source as at March 2015	**Capacity (MW)**	**Capacity %**
Hydro Power	820.6	37.69
Fossil Fuels (Thermal)	717	32.93
Geothermal	588	27.01
Bagasse Cogeneration	26	1.17
Wind	25.5	1.17
Total	**2177.1**	**100**

Source (KNBS, 2016)

2.1.2 Energy Supply in Laikipia County.

In Laikipia County, the national power grid serves only 22 centers and is yet to reach 55 centers. A total of 18% of residents in Laikipia County use electricity as their main source of lighting. A further 35% use lanterns, and 34% use tin lamps. 5% use fuelwood. Electricity use is slightly more common in male-headed households at 19% as compared with female-headed households at 16%. On the other hand, only 4% of residents in Laikipia County use LPG for cooking. A further 3% use paraffin, 66% use firewood and 26% use charcoal. Firewood is the most common cooking fuel by either gender-headed households with 64% of male-headed households and 70% in female-headed households. (Ngugi *et al*., 2013).

The traditional sources of energy still remain popular despite the fact that their supplies are dwindling. Most of the firewood consumed is usually collected from non-forest sources (split-wood, branches and twigs), whilst others purchase firewood. Once in a while, the forest authority allows the neighboring households to collect firewood from the forest especially when they have pruned the trees. Charcoal, also as a popular source of energy is purchased by most of the residents for use.

LPG, though not readily available in the shopping centres, is purchased by the higher income earners living in the County, in the nearby towns. To add on that, paraffin in the county is readily available in the nearby shopping centres at affordable rates, therefore the residents are able to purchase paraffin for both lighting and cooking.

2.2 The concept of Green Energy

Renewable energies are sources of clean, inexhaustible and increasingly competitive energy. They differ from fossil fuels principally in their diversity, abundance and potential for use anywhere on the planet, but above all, in that, they produce neither greenhouse gases – which cause climate change – nor polluting emissions. Their costs are falling and at a sustainable rate, whereas the general cost trend for fossil fuels is in the opposite direction in spite of their present volatility.

Growth in clean energies is unstoppable, as reflected in statistics produced in 2015 by the IEA: they represented nearly half of all new electricity generation capacity installed in 2014, when they constituted the second biggest source of electricity worldwide, behind coal.

Renewable energies include:

- **Wind energy**: the energy obtained from the wind
- **Solar energy**: the energy obtained from the sun. The main technologies here are solar photovoltaic (using the light from the sun) and solar thermal (using the sun's heat)
- **Hydraulic or hydroelectric energy**: energy obtained from rivers and other freshwater currents
- **Biomass and biogas**: energy extracted from organic material
- **Geothermal energy**: heat energy from inside the Earth
- **Tidal energy**: energy obtained from the tides
- **Wave energy**: energy obtained from ocean waves

Renewable energies received important backing from the international community through the Paris Accord signed at the World Climate Summit held in the French capital in December 2015. The agreement, which will enter into force in 2020, establishes, for the first time in history, a binding global objective. Nearly 200 signatory countries pledged to reduce their emissions so that the average temperature of the planet at the end of the current century remains "well below" 2 °C, the limit above which climate change will have more catastrophic effects. The aim is to try to keep it to 1.5 °C.

Likewise, the transition to an energy system based on renewable technologies will have very positive economic consequences. According to IRENA, doubling the renewable energy share in the world energy mix, to 36% by 2030, will result in additional global growth of 1.1% by that year (equivalent to 1.3 trillion dollars), an increase in wellbeing of 3.7% and in employment in the sector of up to more than 24 million people, compared to 9.2 million today.

Main advantages of clean energies:

- **The indispensable partner in the fight against climate change.** Renewables do not emit greenhouse gases in energy generation processes, making them the cleanest, most viable solution to prevent environmental degradation.

- **Inexhaustible**. Compared to conventional energy sources such as coal, gas, oil and nuclear - reserves of which are finite - clean energies are just as available as the sun from which they originate and adapt to natural cycles, hence their name "renewables". This makes them an essential element in a sustainable energy system that allows development today without risking that of future generations.

- **Reducing energy dependence**: the indigenous nature of clean sources gives local economies an advantage and brings meaning to the term "energy independence". Dependence on fossil fuel imports results in subordination to the economic and political short-term goals of the supplier country, which can compromise the security of energy supply. Everywhere in the world, there is a renewable resource – whether that be the wind, sun, water or organic material – available for producing energy sustainably.

- **Increasingly competitive**. The main renewable technologies – such as wind and solar photovoltaic – are drastically reducing their costs, such that they are fully competitive with conventional sources in a growing number of locations. Economies of scale and innovation are already resulting in renewable energies becoming the most sustainable solution, not only environmentally but also economically, for powering the world.

- **Benefiting from a favorable political horizon**. Decisions adopted at COP 21 have shone the spotlight firmly on renewable energies. The international community has understood its obligation to firm up the transition towards a low-carbon economy in order to guarantee a sustainable future for the planet. The international consensus in favor of the "de-carbonization" of the economy constitutes a very favorable framework for the promotion of clean energy technologies.

2.3 Wind Farms and their Location

A wind farm is a group of wind turbines in the same location used to produce electricity. A large wind farm may consist of several hundred individual wind turbines and cover an extended area of hundreds of square miles, but the land between the turbines may be used for agricultural or other purposes. A wind farm can also be located offshore (Manwell *et al*., 2010)

Plate 1: The Lake Turkana Wind Farm in Marsabit, Kenya

As a general rule, economic wind generators require a wind speed of 4.5 m/s (16 km/h) or greater. An ideal location should have a near constant flow of non-turbulent wind throughout the year, with a minimum likelihood of sudden powerful bursts of wind. An important factor of turbine siting is also access to local demand or transmission capacity.

Usually, sites are screened on the basis of a wind atlas and validated with wind measurements. Meteorological wind data alone is usually not sufficient for accurate siting of a large wind power project. Collection of site-specific data for wind speed and direction is crucial to determining site potential in order to finance the project. Local winds are often monitored for a year or more, and detailed wind maps constructed before wind generators are installed.

In general, a distance of 7D (7 × Rotor Diameter of the Wind Turbine) is set between each turbine in a fully developed wind farm, but micro-siting optimizes placement, particularly in hilly areas. Construction of a land-based wind farm requires access the collector system and substation, and possibly access roads to each turbine site.

The wind blows faster at higher altitudes because of the reduced influence of drag. The increase in velocity with altitude is most dramatic near the surface and is affected by topography, surface roughness, and upwind obstacles such as trees or buildings. Typically, the increase of wind speeds with increasing height follows a wind profile power law, which predicts that wind speed rises proportionally to the seventh root of altitude as shown in equation 1 below. Doubling the altitude of a turbine, then, increases the expected wind speeds by 10%, and the expected power by 34%.

$$\frac{u}{u_r} = \left(\frac{z}{z_r}\right)^{\alpha}$$

Equation 1

Where u is the wind speed (m/s) at height z (meters) and u_r is the known wind speed at a reference height Z_r. The exponent (α) is an empirically derived coefficient that varies dependent upon the stability of the atmosphere. For neutral stability conditions, α is approximately 1/7, or 0.143.

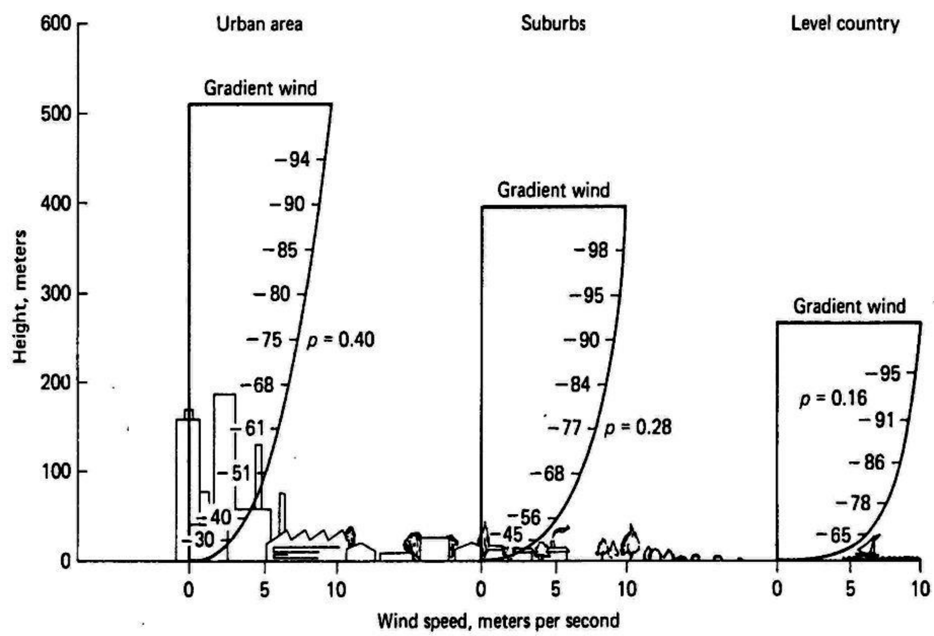

Figure 1: Changes in wind speed as influenced by height and roughness of terrain

Wind turbines are large and heavy, so the access roads and tracks to the site need to be capable of taking oversize loads with no weak bridges, excessively tight corners or steep gradients. Obviously, as the proposed turbine gets larger, the size of the constituent parts that have to be delivered get larger and the access requirements more stringent.

Onshore turbine installations in hilly or mountainous regions tend to be on ridgelines generally three kilometers or more inland from the nearest shoreline. This is done to exploit the topographic acceleration as the wind accelerates over a ridge. The additional wind speeds gained in this way can increase energy produced because more wind goes through the turbines. The exact position of each turbine matters, because a difference of 30m could potentially double output. This careful placement is referred to as 'micro-siting'.

Offshore wind turbines are less obtrusive than turbines on land, as their apparent size and noise are mitigated by distance. Because water has less surface roughness than land (especially deeper water), the average wind speed is usually considerably higher over open water. Capacity factors (utilization rates) are considerably higher than for onshore locations, which is the ratio of actual productivity in a year to the theoretical maximum.

2.4 The Multi-Criteria Decision-Making Process

Finding suitable sites for wind farms is a complex decision-making problem, involving several, sometimes conflicting, criteria and multiple objectives. MCDM methods provide a logical framework to investigate, analyze, and solve such problems (Badea *et al*., 2017). The AHP approach, which is used in our study, is a utility function-based MCDM method. and is one of the most frequently applied MCDM approaches which has already been successfully used to solve various decision-making problems in fields such as public administration and policy decision-making, or renewable energy analysis, among others (Abu Taha and Daim, 2013; Forman and Gass, 2001; Pohekar and Ramachandran, 2004; Saaty, 2008).

AHP, introduced by Thomas Saaty (1987), is a systematic procedure of evaluating the relative importance of a set of criteria in order to achieve a certain goal. It is an effective tool for dealing with complex decision making and may aid the decision maker to set priorities and make the best decision. By reducing complex decisions to a series of pairwise comparisons, and then synthesizing the results, AHP helps to capture both subjective and objective aspects of a decision. In addition, AHP incorporates a useful technique for checking the consistency of the decision maker's evaluations, thus reducing the bias in the decision-making process.

AHP considers a set of evaluation criteria and a set of alternative options among which the best decision is to be made. It is important to note that, since some of the criteria could be contrasting, it is not true in general that the best option is the one which optimizes every single criterion, rather the one which achieves the most suitable trade-off among the different criteria.

AHP generates a weight for each evaluation criterion according to the decision maker's pairwise comparisons of the criteria. The higher the weight, the more important the corresponding criterion. Next, for a fixed criterion, AHP assigns a score to each option according to the decision maker's pairwise comparisons of the options based on that criterion. The higher the score, the better the performance of the option with respect to the considered criterion. Finally, AHP combines the criteria weights and the options scores, thus determining a global score for each option, and a consequent ranking. The global score for a given option is a weighted sum of the scores it obtained with respect to all the criteria.

AHP can be implemented in three simple consecutive steps:

- Development of the pairwise comparison matrix
- Normalization of the resulting matrix
- Determination of the corresponding weights
- Determination of the consistency ratios

Each of the above-mentioned steps is described in detail further in chapter 3.

2.5 Case studies

In this section, three case studies of GIS-based models for wind energy facility site selection used in the USA, the UK, and South Africa respectively have been selected to illustrate how GIS has been applied by planners and decision-makers across the world. These three models have been selected as they represent different geographic locations and contexts. The three models were also selected because of their use of GIS for constraints mapping and varied use of weighting procedures. A description of each model is given below, taking into account the different assessment criteria used and approach taken to determining site suitability.

2.5.1 The USA

Rodman and Meentemeyer (2006), proposed a rule-based method (based on known processes) using GIS to analyze the suitability of wind energy developments in Northern California. The approach was a geographic analysis of wind energy facilities already developed and sites proposed so that energy planners can use the information to predict the extent to which wind energy can be developed further based on land availability and public perception.

Methodology

The criteria used included, physical features such as wind resources, obstacles, and terrain; Environmental factors such as land use, vegetation and sensitive areas like wetlands and presence of endangered plant species; and human impact factors such as proximity to development and public recreational areas.

Three models were developed (physical, environmental, human) using expert judgment to score and weight the individual layers that influenced decisions. Each data layer (such as average wind speed or vegetation) was then assigned a weight that represented its significance to the overall suitability measurement. The most important criterion was assigned the highest weight.

Results

Each of the three models resulted in a map with scores ranging from Poor (1); Fair (2); Good (3) to Excellent (4). Locations with a suitability score of 0 were considered to be unsuitable for any combined model that included the individual model.

The physical and environmental models were combined and compared to the physical model alone, and all three models were combined and compared with the physical and environmental combination.

The results of the analysis showed that the criteria and their respective scores do impact the amount of land available for wind energy development. Rodman and Meentemeyer (2006) concluded that the large-scale suitability model could be improved by including additional factors such as visibility analysis and mapping of bird migration corridors.

2.5.2 The UK

Dunsford, Macfarlane, and Turner (2003) developed a regional GIS to support the development of the North East of England Renewable Energy Strategy.

Methodology

A GIS cartographic model was created to evaluate options for the location of onshore wind energy facilities using the following input layers: Wind speed, Utilities, Infrastructure, Landscape Issues, Radar and Communication and Military training and operations. According to Dunsford, Macfarlane, and Turner (2003), this model was chosen as it allowed the Boolean combination of “layers” of information containing data relating to constraints or restrictions on wind energy development with the result being pockets of areas considered suitable for wind energy facilities based on the input criteria.

The cartographic model was divided into three separate models which included the GIS constraints model, visibility analysis, and the landscape Appraisal.

Scenarios were then modeled by combining the models such as the GIS constraints model and Visibility Analysis. The visual impact and areas preferred for wind energy development were displayed on a map.

Results

The combination of the GIS constraints model together with the Landscape Appraisal provided locations where a landscape was less sensitive to wind energy development and where there was little constraint to wind energy developments.

2.5.3 South Africa

The rationale for developing the methodology was so that planning zones could be delineated identifying specific areas for wind energy development. International precedence, such as the Government Office for the North East study (North East Assembly, 2009), was chosen as a starting point for selecting the methods of assessment and which were then adapted to suit the local context.

Methodology

The process model to develop a wind energy plan using layers such as environmental criteria, planning criteria, infrastructure and landscape criteria, cultural and landscape criteria was developed. The various layers were combined in a "sieve" analysis using GIS. The final output was subjected to a cumulative impact assessment analysis, after which recommended wind energy zones were illustrated in a regional wind energy plan.

Three separate models which included The GIS constraint model, Visibility Analysis and Landscape Appraisal were used.

Results

The resultant composite map, based on a rating system related to criteria importance and landscape sensitivity, defined the preferred wind energy zones. The study area for this assessment was largely undeveloped with open landscapes and in order to avoid being able to see one wind energy facility from the next, which would be the cumulative impact, buffers of 30 km or 50 km around wind energy facilities were proposed as an additional layer to the composite map.

Table 2: Overview of Case Studies

Location	**USA**	**UK**	**South Africa**
Purpose of the study	Evaluation and validate whether already existing wind energy facilities were indeed located in ideal wind energy development zones to use this information for placing future wind energy facilities more strategically.	Adopted to promote wind energy as part of a renewable energy strategy for the North Eastern region of England by locating potential areas for wind energy development.	A proposed methodology for the strategic site selection of wind energy facilities in the Western Cape province of South Africa in order to preserve the quality of the landscapes whilst promoting wind energy development in the region.
Constraints Model	Physical, environmental and human	Technical and environmental	Technical and environmental
Wind Resource Layer	Yes	Yes	No
Grid Connection Layer	No	Yes	No
Land Appraisal	No	Yes	Yes
Visibility Analysis	No	Yes	Yes
Weighting and Scoring System	Scores were assigned using expert judgment. The scoring ranged from 0 = Unsuitable, 1 = Poor, 2 = Fair, 3 = Good and 4 = Excellent for attributes of the physical, environmental and human models.	Constraints classified either as absolute of zones of consultation; visibility map showing grid cells with the highest values as the most visible areas and landscape appraisal ratings of low (1) to high (5) sensitivity.	Negative criteria result in restricted or highly restricted areas and presence of positive criteria will result in preferred to highly preferred areas. The presence of any negative criteria will result in restriction regardless of any positive criteria.
Sensitivity Analysis	Display of different combinations used to show the effect of each criterion such as physical and environmental impacts versus only physical features and allows the decision maker to draw conclusions on the importance of including more than one criterion	The constraints model was combined with the visibility analysis to determine whether it would be visually acceptable in a preferred area and the combination of the constraints model with the landscape appraisal.	The constraints model was combined with the landscape assessment (including visual assessment) and the final output subjected to a cumulative impact assessment analysis.

3. METHODOLOGY

3.1 The Study Area

Laikipia County is a vast plateau to the north-west of snow-capped Mount Kenya, straddling the equator at the heart of Kenya’s Rift Valley Region. It spans an area of over 9,500km². The plateau extends from the foothills of Mount Kenya to the wall of the Rift Valley at Lake Baringo and stretches northwards towards Samburuland. These plains are physically diverse and scenically spectacular, covered by open grasslands, basalt hills, lonely kopjes and dense cedar forests, fed by the Ewaso Nyiro and Ewaso Narok rivers. Laikipia County is ranked as the 15th largest county in Kenya based on the land size and borders seven counties namely: Samburu to the North; Isiolo to the North East; Meru to the East; Nyeri to the South East; Nyandarua and Nakuru to the South West; and Baringo to the West.

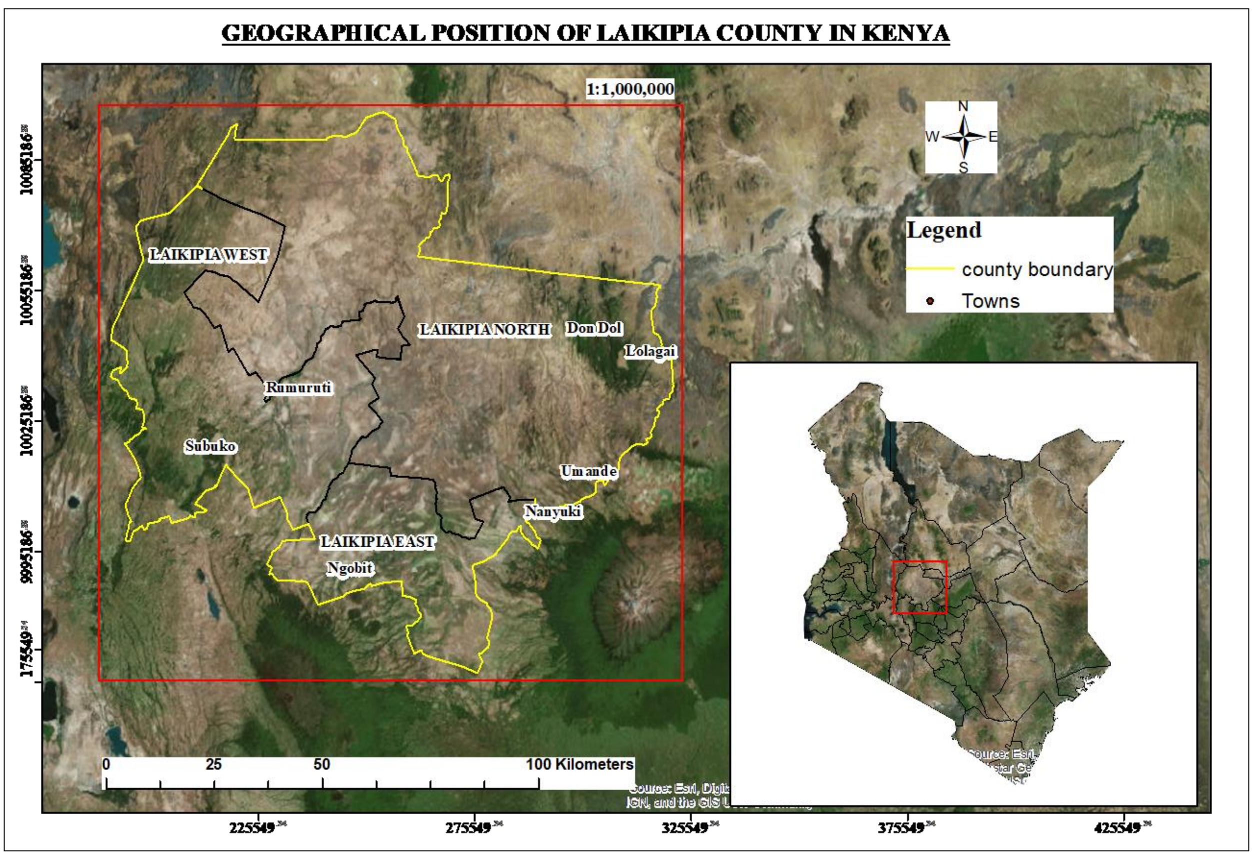

Figure 2: Geographical position of Laikipia county in Kenya

The soils in the county are mainly loam, sand and clay. Black cotton soil which has inherent fertility is found in most parts of the plateau. The dark reddish brown to red friable soils and rocky soils are mainly found on the hillsides. The main economic activity in the county consists of tourism and agriculture, chiefly grain crops, ranching and greenhouse horticulture, and the county experiences a cool, temperate climate with both rainy and dry seasons.

The altitude of Laikipia County varies between 1,500 m above sea level at Ewaso Nyiro basin in the North to a maximum of 2,611 m above sea level around Marmanet forest. The county's population according to the 2009 National Census is 399,227 with males being 49.8% while female are 50.2% of the population. With multiple ethnic communities, the Kikuyus and Maasai communities form the largest portion of its residents. Other tribes mainly Borana, Samburu, Kalenjin, Meru, Somali, Turkana, European and Asian settlers are the resident minorities.

3.2 Summary of the Methodology

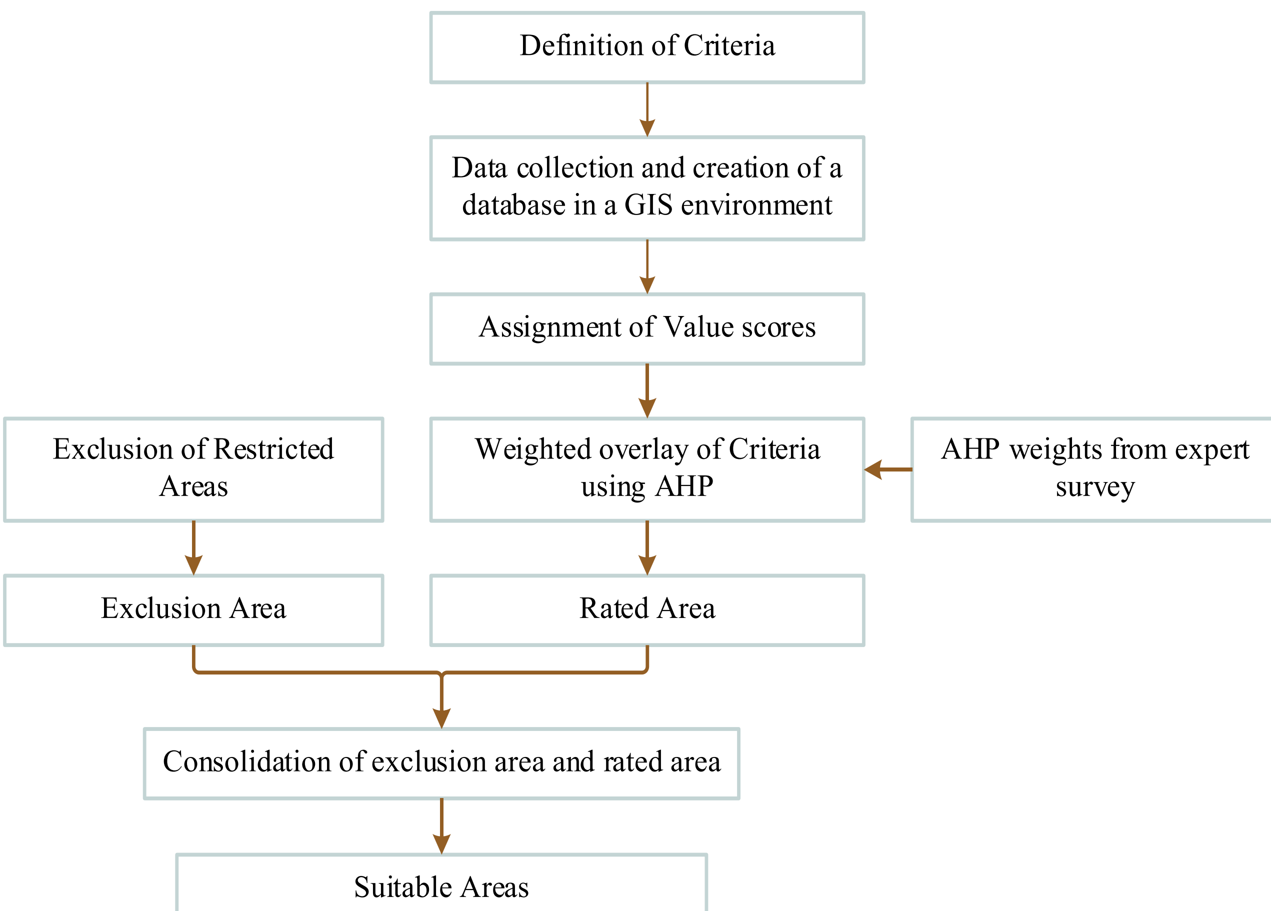

Figure 3: Methodological Framework

3.3 Identification of Decision Criteria

The wind farm planning process often incorporates complexity, uncertainty, multiple management objectives and various spatial data attributes. Moreover, in order to assess the degree of suitability for a certain potential location, most decision-making processes generally consider multiple criteria.

In this study, decision criteria consist of constraints and factors, which represent quantifiable attributes to assist the decision-making process. The criteria were established based on various scientific publications and expert opinions.

Decision constraints aim to exclude areas deemed ‘unfeasible’ for wind farm development and included wind speed, slope, protected areas and distances to water bodies, built-up areas, road networks and electricity transmission lines. Exclusion zones (unfeasible areas) were therefore denoted a value equal to zero (0) whilst potential development sites (feasible areas) were denoted a value equal to one (1).

Decision factors, on the other hand, are evaluation criteria which aim to describe the degree of suitability for the alternative wind farm locations (grid cells) considering the respective attribute (Hansen, 2005). In this study, they included wind speed, slope, landcover and distances to roads, electricity transmission lines and built-up areas.

3.4 Data Collection

In order to determine reliable sites for the potential development of wind farms in Laikipia County, proper data should be collected and analyzed. Several sources are utilized not only for the wind speed data, but also for administrative boundary data, road network, electricity transmission network, elevation, land cover information and protected areas. The data sources used for the completion of the project are presented in the following paragraphs Most datasets were acquired in vector format; however, data on elevation, land cover and wind speed were obtained in raster format.

a) Wind Speed

Onshore data on wind speed at 100m hub heights above the surface for Kenya were obtained from The ‘Global Atlas for renewable energy’ of IRENA web portal at a 1km spatial resolution. Global Wind Atlas data of IRENA is the most suitable to use since the layers were produced using microscale modelling in the Wind Atlas Analysis and Application Program (WAsP). The data captured small-scale spatial variability of winds speeds due to high-resolution orography (terrain elevation), surface roughness and surface roughness change effects.

Another data source for wind speed distribution was the Kenya Meteorology Department. They provided daily wind speed data at 10m height from January 2000 to December 2016 for their stations at Meru, Nanyuki, Nyahururu and Nyeri which was used to validate the wind speed data obtained from the Global Wind Atlas.

b) Land Cover

Land cover data was obtained from the Climate change Initiative Land Cover team. The team successfully developed a prototype high-resolution LC map at 20m over Africa based on 1 year of Sentinel-2A observations from December 2015 to December 2016. The Coordinate Reference System used for the global land cover database is a geographic coordinate system (GCS) based on the WGS-84 reference ellipsoid.

c) Elevation

The elevation raster dataset, published on 16th of April 2015, was obtained from the online data portal for Regional Centre for Mapping Resource for Development

The data represents a 30 meters Digital Elevation Model (DEM) from Shuttle Radar Topography Mission (SRTM), derived through mosaicking of individual SRTM tiles for Kenya and clipping the mosaicked tiles using its boundary extent.

d) Electricity Transmission Network

The ongoing and proposed high voltage transmission (132 KV) lines for Laikipia county were obtained from Kenya Electricity Transmission Company Limited (KETRACO) in the form of vector data.

e) Road Network and County Boundary.

The vector layers of the road networks and county boundary were digitized by using survey of Kenya topographic sheets (Sheet Numbers: 91-2, 92-1, 92-2, 91-4, 92-3, 92-4, 93-3, 93-4, 105-1, 105-2, 106-1, 106-2, 107-1, 107-2, 105-4, 106-3, 106-4, 107-3, 107-4, 119-2, 120-1, 120-2, 121-1, 120-4), all at the scale of 1:50000.

f) Protected Areas

The vector layer on protected areas was obtained from The World Database on Protected Areas. It is a foundation dataset for conservation decision-making.

Description of Decision Criteria

a) Wind speed:

The average wind speed in a given area is a key criterion regarding the determination of the economic performance of a wind turbine. Therefore, the wind energy potential criterion is incorporated in almost every study and is considered to be one of the most important criteria (Bennui *et al*., 2007; Gorsevski, *et al*., 2013; Janke, 2010; Rodman and Meentemeyer, 2006; Tegou *et al*., 2010; Van Haaren and Fthenakis, 2011; among others).

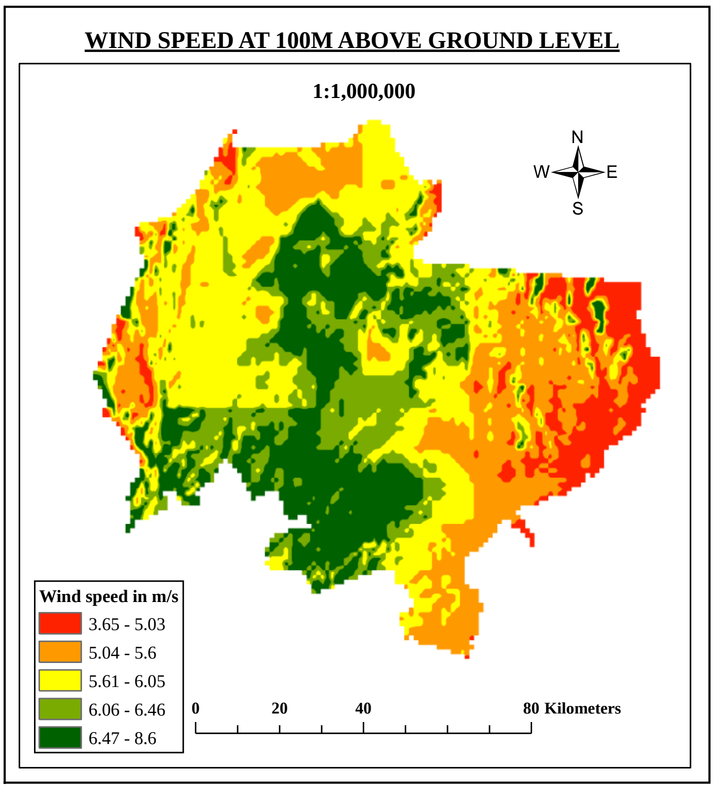

Figure 4: Wind Speed at 100m above ground level

Figure 4, illustrates the distribution of annual average wind speeds in the study area. According to this data, the annual average wind speeds at a height of 100 m above ground level, range from 3.65 m/s to 8.60 m/s, although wind speeds below 3.65 m/s and above 8.60 m/s rarely occur. Previous scientific publications commonly apply a minimum threshold value of 4.5 m/s (Latinopoulos and

Kechagia, 2015) or 5 m/s (Baban and Parry, 2001). In this study, areas with a modelled wind speed lower than 5 m/s were deemed unfeasible for wind farm development according to the opinions of regional wind farm planners and hence excluded. Average wind speeds above 7.0 m/s were considered to be well suited, which matches with the value score scheme shown in Table 3. According to this scheme, lower wind speeds received value scores of 2 to 4 and higher wind speeds, value scores of 6 to 10.

b) Land cover:

Suitability of an area for the siting of wind turbines also depends on the prevalent land cover type. From a social acceptance point of view, some land cover types can be considered preferable to others. It is recognized in other literature that 'shorter' vegetation is preferable to 'taller' species. Thus, agricultural land, barren land, grassland, and shrubland can generally be considered to be most suitable, whereas forestland is considered to be less suitable (Gorsevski *et al*., 2013; Janke, 2010; Rodman and Meentemeyer, 2006; Tegou *et al*., 2010; Van Haaren and Fthenakis, 2011).

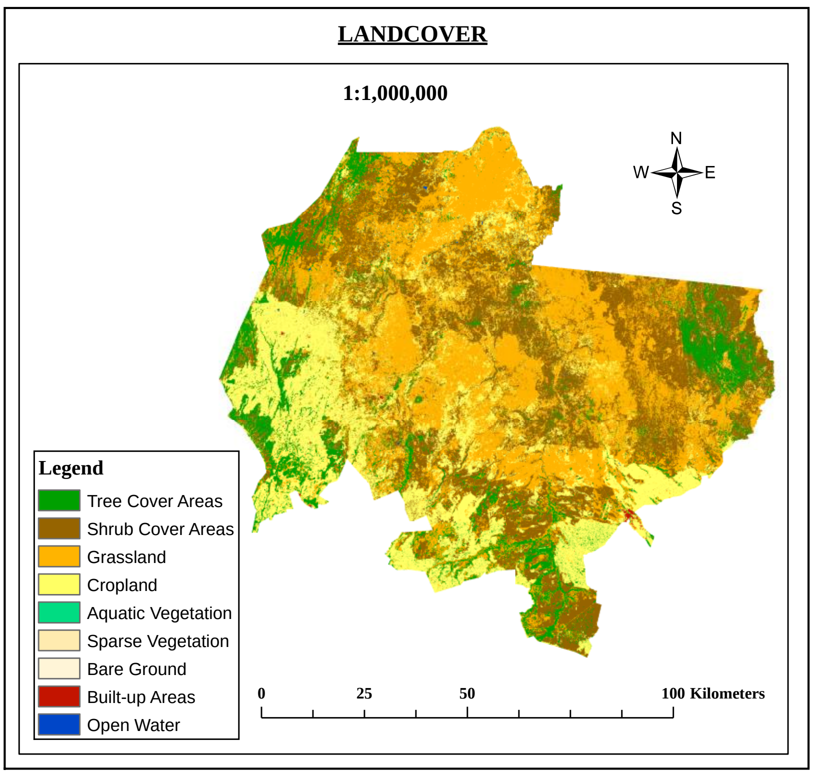

Figure 5: Land Cover in Laikipia County

In order to assign value scores to the prevalent land cover types in Laikipia, local experts were asked to evaluate the relative suitability of each land cover type using a nine-point scale, after having been previously classified as shown in Figure 5. Higher value scores were assigned to areas that might be perceived as being better suited for wind power projects (also from a social acceptance point of view), such as agricultural land, barren land, grassland, and shrubland. The membership value assigned to each land cover group is detailed in Table 3.

c) Built-up areas:

The siting of wind turbines in or close to urban areas is not advisable due to noise nuisance and visual intrusion or massing effects caused by wind turbines. Regarding the problem of noise nuisance, there are strict regulations concerning the maximum sound pressure level allowed in urban areas. According to the existing regulations by the National Environmental Management Authority (NEMA), the maximum sound pressure level allowed at night is 40 dB in residential areas and 45 dB in mixed-use areas. To prevent massing effects, areas closer than 550 m to residential areas were excluded.

Further, potential visual impacts such as landscape impacts, shadow flicker, or light reflections, have to be considered as these are also subjects of concern regarding the social acceptance at the local level. In order to minimize these visual impacts, areas further away from urban are deemed more feasible than potential wind farm sites close to urban areas. Gorsevski *et al* (2013) and Rodman and Meentemeyer (2006) solely exclude the developed area itself without a buffer zone around it; however, buffer zones in other studies range between 500 and 2000 m depending on the type of area (large city, town e.t.c) or number of residents (Baban and Parry, 2001; Hansen, 2005; Aydin *et al*., 2010; Latinopoulos and Kechagia, 2015).

Opinions of local experts about possible threshold distances, beyond which visual impacts would not affect the locals, varied, but mostly ranged between 1,000 m and 2,000 m. Therefore, for the purpose of this study built-up areas (incorporating populated places and towns), including a 2000 m buffer, were deemed unfeasible for wind farm development and hence excluded. Accordingly, areas in excess of 2,000 m received the highest value score of 10. Below that distance threshold, value scores diminished with decreasing distance to urban areas as shown in Table 3.

d) Slope gradient:

Steep slopes of a surface can reduce the accessibility of cranes and trucks and increase construction costs. In this study, the threshold value for slope gradient ranged between 20% and 2%, considering both the economic feasibility (accessibility) and the minimization of potential environmental impacts from erosion and soil loss. This also corresponded to the opinions of the regional wind power experts and wind farm planners who participated in the conducted survey. Lower slopes are preferred and received higher value scores as shown in Table 3. Figure 6 illustrates the distribution of slope in the study area.

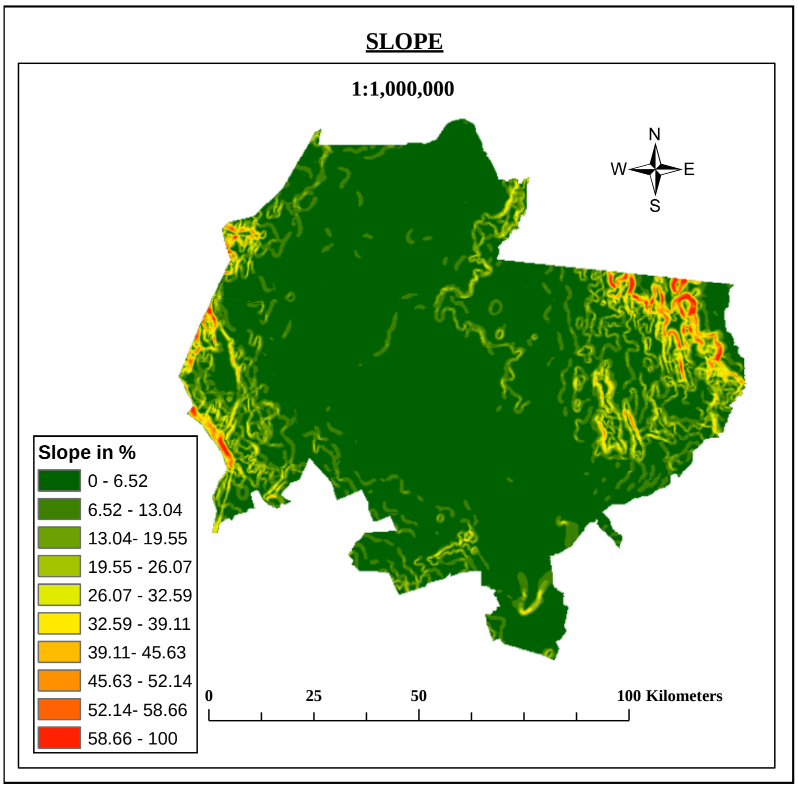

Figure 6: Slope in Laikipia County

e) Protected Areas:

This criterion comprises of parks, reserves, water bodies, conservancies, ranches, protected forests and wetlands. These areas serve the protection of nature and wildlife and are therefore excluded from wind energy development. Figure 7 shows the distribution of protected areas in Laikipia County.

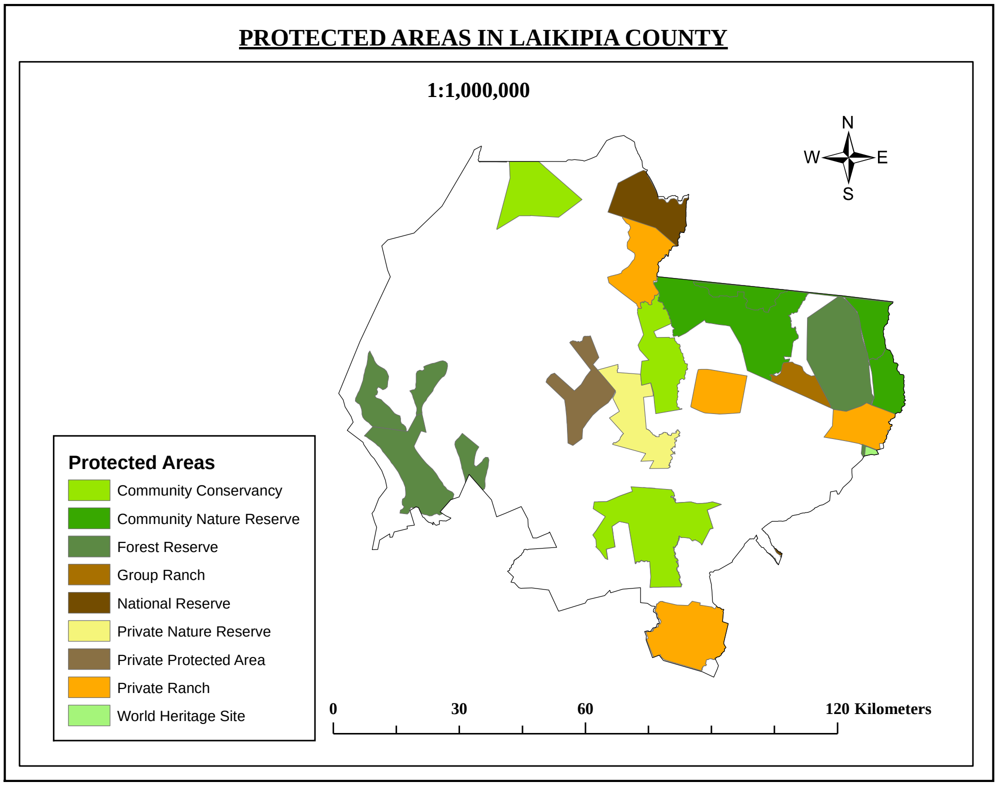

Figure 7: Protected Areas

A major concern is the potential collision of birds and bats with wind turbine blades if wind turbines are located too close to their habitats or migratory routes. Baban and Parry (2001) identified in their study that a 1000 m buffer from areas of ecological value should be applied, as well as a buffer of 400 m from water bodies. In this study, inland waters, including a 400m buffer, as well as the above mentioned ecologically significant areas, including a 1000 m buffer, were deemed unfeasible for wind farm development and hence excluded. Above that distance threshold, value scores increased with increasing distance from protected areas.

f) Electricity transmission network:

In order to reduce the costs associated with cabling and electricity losses over long transmission distances, wind farms should be located in the proximity of the electricity grid. Figure 8 shows the distribution of the proposed and ongoing electricity transmission network in Laikipia County.

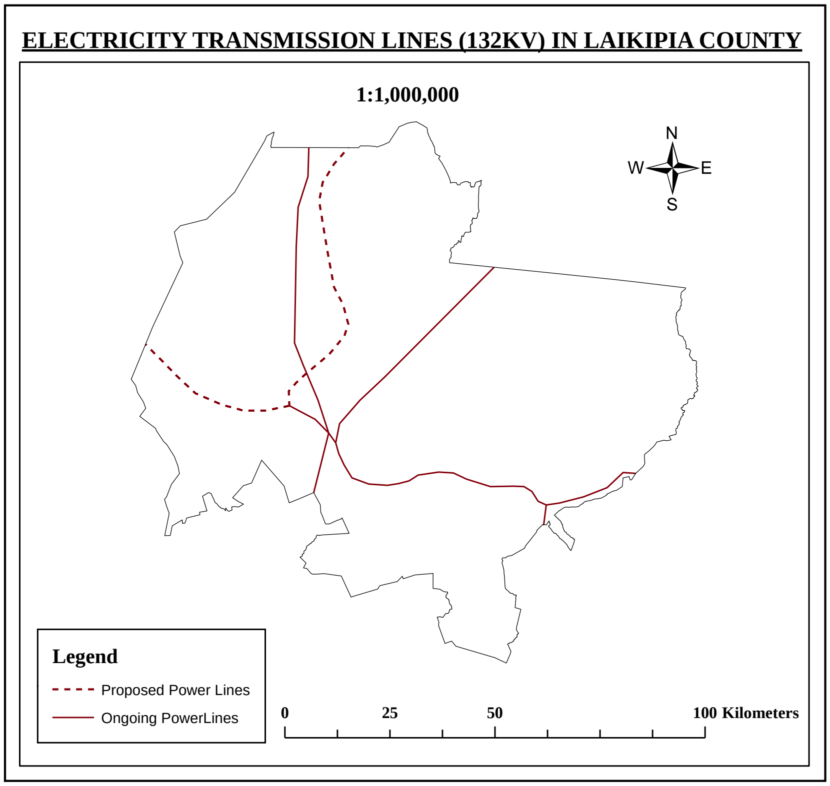

Figure 8: Electricity Transmission Network

Rodman and Meentemeyer (2006), Aydin *et al*. (2010), and Bennui *et al*. (2007) do not include the distance to the electricity grid in their analyses. Van Haaren and Fthenakis (2011) calculate the costs associated with the connection of a wind turbine to the electricity grid. Among the studies considered, only Gorsevski *et al*. (2013), Tegou *et al*. (2010) and Janke (2010) include the distance from the electricity grid as a criterion in their analyses. However, the determined maximum distance of wind turbines to the electricity grid strongly varies throughout various literature. Tegou *et al*. (2010) set the maximum threshold to 2,000 m, whereas Gorsevski *et al*. (2013) set it to 20,000 m. The distance to the electricity grid seems to be highly dependent on the location of the study area.

In this study, areas closer than 100m to the power line were determined as restricted areas. Above that minimum distance, the value score increased with decreasing distance from the grid. Based on the spatial dimension and characteristics of our study area, areas within the range of 100 to 1,000 m received the highest value score of 10, and areas with distances in excess of 9,000 m, the lowest score of 1. It should also be noted that this decision factor only includes the high voltage transmission network (132KV) and does therefore not represent all opportunities for wind farms to connect to the electricity grid.

g) Proximity to road network:

To reduce construction costs for new access roads and to avoid soil sealing, wind turbines should be located as closely as possible to the existing road network and the roads must have a minimum width of 4 m and a solid pavement (Van Haaren and Fthenakis, 2011). Figure 9 shows the road network for Laikipia County.

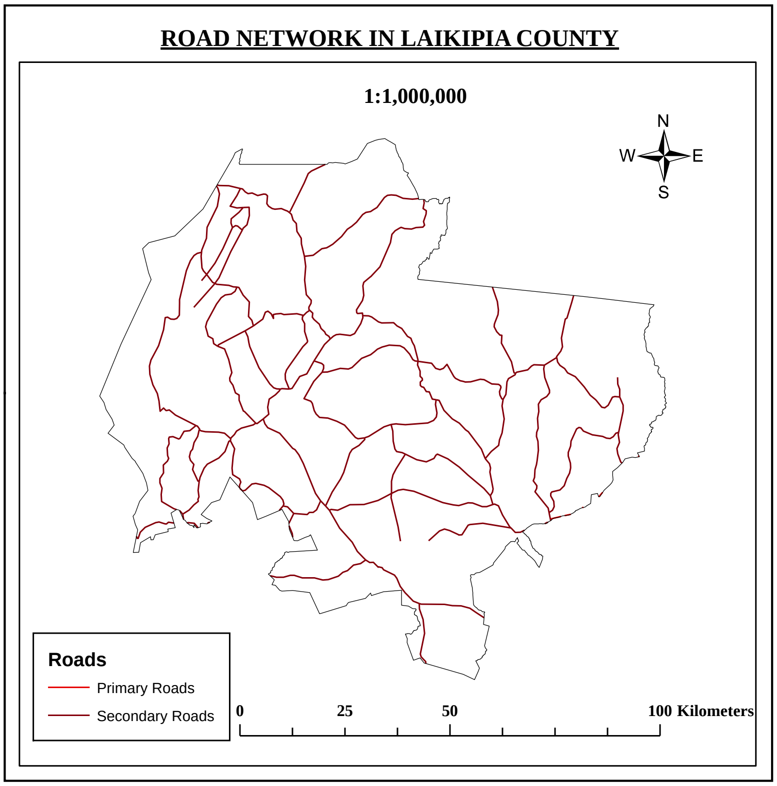

Figure 9: Road Network

In most wind farm siting assessments, the areas further away from roads are considered less suitable than those closer to roads (Baban and Parry, 2001; Gorsevski *et al*., 2013; Hansen, 2005; Janke, 2010; Tegou *et al*., 2010; Van Haaren and Fthenakis, 2011). However, there is no generally valid definition of a maximum distance from the wind turbines to the road network. Bennui and Rattanamanee (2007) as well as Tegou *et al*. (2010), for instance, set the maximum distance to the next road to 2,500 m, whereas in contrast, Baban and Parry (2001) and Gorsevski *et al*. (2013) set it to 9,000 m and 10,000 m, respectively. The road network in Laikipia is not quite dense. Based on this fact, areas with a larger distance than 9000 m from roads received the lowest value score of 1. The value scores increased with decreasing distance.

Table 3: Value Score per criterion

Value Score	**Wind Energy (m/s)**	**Distance from road Network (m)**	**Distance from electricity grid (m)**	**Slope of terrain (%)**	**Distance from built-up areas (m)**	**Land cover Type**
0	<5.0	<500	0-100	>20	0-1600	
1		>9000	>9000	18-20	1600-3000	Open Water
2	5.0-5.50	8000-9000	8000-9000	16-18	3000-4000	Bare Areas
3		7000-8000	7000-8000	14-16	4000-5000	Grassland
4	5.50-6.00	6000-7000	6000-7000	12-14	5000-6000	Shrub-Cover Areas
5		5000-6000	5000-6000	10-12	6000-7000	Sparse Vegetation
6	6.50-7.00	4000-5000	4000-5000	8-10	7000-8000	Cropland
7		3000-4000	3000-4000	6-8	8000-9000	Tree Cover Areas
8	7.00-7.50	2000-3000	2000-3000	4-6	9000-10000	Aquatic Vegetation
9		1000-2000	1000-2000	2-4	10000-11000	Built-up Areas
10	>7.50	500-1000	100-1000	0-2	>11000	

3.5 Determination of Criteria Weights

After identifying the influential criteria, the relative importance or the weighting of individual criteria was performed. In this study, AHP as a most popular and structured method was used. Developing the weights for criteria required four basic steps:

a) Development of pairwise Comparison Matrix

A matrix, A, an m×m real matrix, where m is the number of evaluation criteria considered, was developed. Each entry a_{jk} of the matrix A represented the importance of the j^{th} criterion relative to the k^{th} criterion. If $a_{jk} > 1$, then the j^{th} criterion was more important than the k^{th} criterion, while if $a_{jk} < 1$, then the j^{th} criterion was less important than the k^{th} criterion. If two criteria had the same importance, then the entry a_{jk} was 1. The entries a_{jk} and a_{kj} satisfied the constraint shown in equation 2.

$$a_{jk} \cdot a_{kj} = 1 \qquad \text{Equation 2}$$

Obviously, $a_{jj} = 1$ for all j. The relative importance between two criteria was measured according to a numerical scale from 1 to 9, as shown in Table 4. The phrases in the “Interpretation” column of Table 4 are only suggestive and were used to translate the decision maker’s qualitative evaluations of the relative importance between two criteria into numbers.

Table 4: Scale for Comparison

Value of a_{jk}	**Interpretation**
1	Two factors contribute equally to the objective
3	Experience and judgement slightly favor one over the other
5	Experience and judgement strongly favor one over the other
7	Experience and judgement very strongly favor one over the other. Its importance is demonstrated in Practice
9	The evidence favoring one over the other is of the highest possible validity
2,4,6,8	When compromise is needed

b) Normalizing the Resulting Matrix

Once the matrix A was built, the normalized pairwise comparison matrix A_{norm} was derived by making equal to 1 the sum of the entries on each column, i.e. each entry $\bar{a}_{jk}$ of the matrix A_{norm} was computed as:

$$\bar{a}_{jk} = \frac{a_{jk}}{\sum_{l=1}^{m} a_{lk}} \qquad \text{Equation 3}$$

c) Averaging the values in each row to get the corresponding rating

The criteria weight vector w (an m-dimensional column vector) was estimated by dividing the sum of the normalized row of the matrix by the number of criteria used (n) to generate the weighted matrix.

d) **Calculating the Consistency Ratio**

The evaluation required a certain level of matrix consistency, i.e. that the elements are linear independent. That was assessed by employing the consistency index CI as follows:

- Firstly, the λ_{max} (the highest eigenvalue of the matrix) was calculated as:

$$A * w_j = \lambda_{\max} * w_j \qquad \text{Equation 4}$$

- Then the consistency index (CI) was calculated as per equation 5, where m represents the number of independent rows of the matrix.

$$CI = \frac{\lambda_{\max} - m}{m - 1} \qquad \text{Equation 5}$$

To check if our opinions were consistent in our scoring, the Consistency Ratio, which is a comparison between Consistency Index and Random Consistency Index (RI) was calculated as:

$$CR = CI / RI \qquad \text{Equation 6}$$

An acceptable ratio of consistency of <10%, was expected. Table 5 represents the Random Consistency Indices for various number of items (n) compared in a matrix.

Table 5: Random Consistency Index for number of items compared in a matrix

n	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
RI	0.00	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.51

Since the idea of this study was to incorporate the opinions of several experts with different viewpoints on the optimal siting of wind farms, multiple matrices had to be aggregated. In this case, the priority vectors were computed for each individual and these priority vectors were then aggregated to form the priority vector of the group.

3.6 Data Processing

All the necessary datasets were collected and converted into usable forms using ArcGIS 10.4.1 geo-processing tools. For this type of analysis, working with a grid system was the most effective means of calculating values for particular locations. This way each grid unit (or cell) in the study area would have an integer value and these values could be altered based on the weights assigned to them, yielding a suitability score for each cell.

A final grid resolution of 20.56 m (WGS_1984_UTM_Zone_37S projection) was chosen for this analysis because it was the smallest cell size amongst the datasets, found in the Land Cover raster. All other datasets were resampled to this cell size. To reduce the computation time of processing and analysis, all layers were first clipped to the study areas extent.

Once all the datasets had been converted to a common format (i.e. same coordinate system, same cell size, proper extent, etc.), they were added to a geodatabase in ArcGIS. The geodatabase included feature datasets for Administrative, Infrastructure, and Environmental themes, and includes the raster datasets. Feature topology was not enforced because it was not critical for this analysis at this scale.

3.6.1 Decision Constraints Analysis

Euclidean distances were calculated from each feature to a distance as shown in Table *4*3, producing new rasters as outputs. The new rasters were manually converted to a binary scale (1/0) using the Reclassify tool. Areas within the buffer thresholds were assigned values of zero, while the remaining areas were given a value of one. These outputs were then combined into a single layer through the Raster Calculator tool**.** Areas with values of ‘0’ were discarded at this stage.

A Euclidean Distance/Reclassify tool combination was used instead of a Buffer/Polygon-to-Raster tool combination strictly to save processing time. The Buffer tool only works with feature classes (vector layers), and the large size of the datasets used in this analysis often required a long time to calculate the polygon geometry, and then the new polygon layers would need to be converted back to rasters for the overlay operation, a process that also took a long time for each operation. The Euclidean Distance tool accepts either feature classes or rasters as inputs and produces a raster as an output, thus effectively doing the same thing as buffering in a fraction of the time. The Reclassify tool was used to set the buffer thresholds. A diagram of the Model of this stage is shown in Appendix E.

3.6.2 Multi-Criteria Decision Analysis

A similar approach to decision Constraint analysis was used with the Euclidean Distance tool being used for the distance-dependent criteria, and then all layers were reclassified to a scale compatible with the Weighted Overlay tool in ArcGIS (i.e. 1 through 10 by intervals of 1) and then given a scale value in the Weighted Overlay Table. The AHP-derived criteria weights were then entered into the Weighted Overlay Table prior to running the tool. The output raster from this stage was a suitable areas layer based on the AHP-derived criteria weights. A diagram of the Model of this stage is shown in Appendix F.

3.6.3 Identification of most suitable locations

A mask layer representing all unrestricted areas from decision constraint analysis and the suitable cells from the multi-criteria decision analysis was created and all the non-excluded areas assigned to one of the three suitability classes as shown in Table 6. The output raster from this operation was then converted to polygons so that the geographic area could be calculated, and then polygons larger than 5,000 acres were selected as optimal sites as shown in Figure 15.

Table 6: Suitability Value score

Class	**Value Score**
High	8-10
Medium	5-7
Low	1-4

A 5,000-acre threshold was chosen to accommodate utility-scale wind farms, which according to NREL researchers (Denholm *et al*., 2009), is roughly half a square kilometer for each 2MW wind turbine. This is due to the fact that the area in question must be capable of housing the total area of the turbines as well as the temporary land effects inherent in the construction of the wind farm.

4. RESULTS AND DISCUSSION

4.1 Results

In order to create accurate wind farm suitability maps, it was very important to assign weights to each criterion in a systematic and comprehensive way. For this purpose, two experts in the field of renewable energy and wind power were asked to fill the pairwise comparison table for all criteria and their responses are shown in Appendices A and B.

The result of the overall normalized values, criteria weights (averages), and consistency ratios are shown in Appendices C and D. Table 7 represents the obtained overall criteria weights that were applied in weighted overlay analysis in the GIS environment.

Table 7. Criteria weights

Criteria	**Weight %**
Wind Speed	50.42
Distance from Transmission Network	4.74
Slope	9.22
Distance from Road Networks	3.54
Distance from Built-up Areas	20.41
Landcover	11.68

Individual restriction layers are presented in Figure 10, detailing exclusion zones (unfeasible areas) denoted a value of zero (0) and potential development sites (feasible areas) denoted a value of one (1). The composite restriction layer is presented in Figure 11. In addition, the total area of exclusion zones relating to each decision constraint, as well as the composite restriction layer, is presented in Table 8.

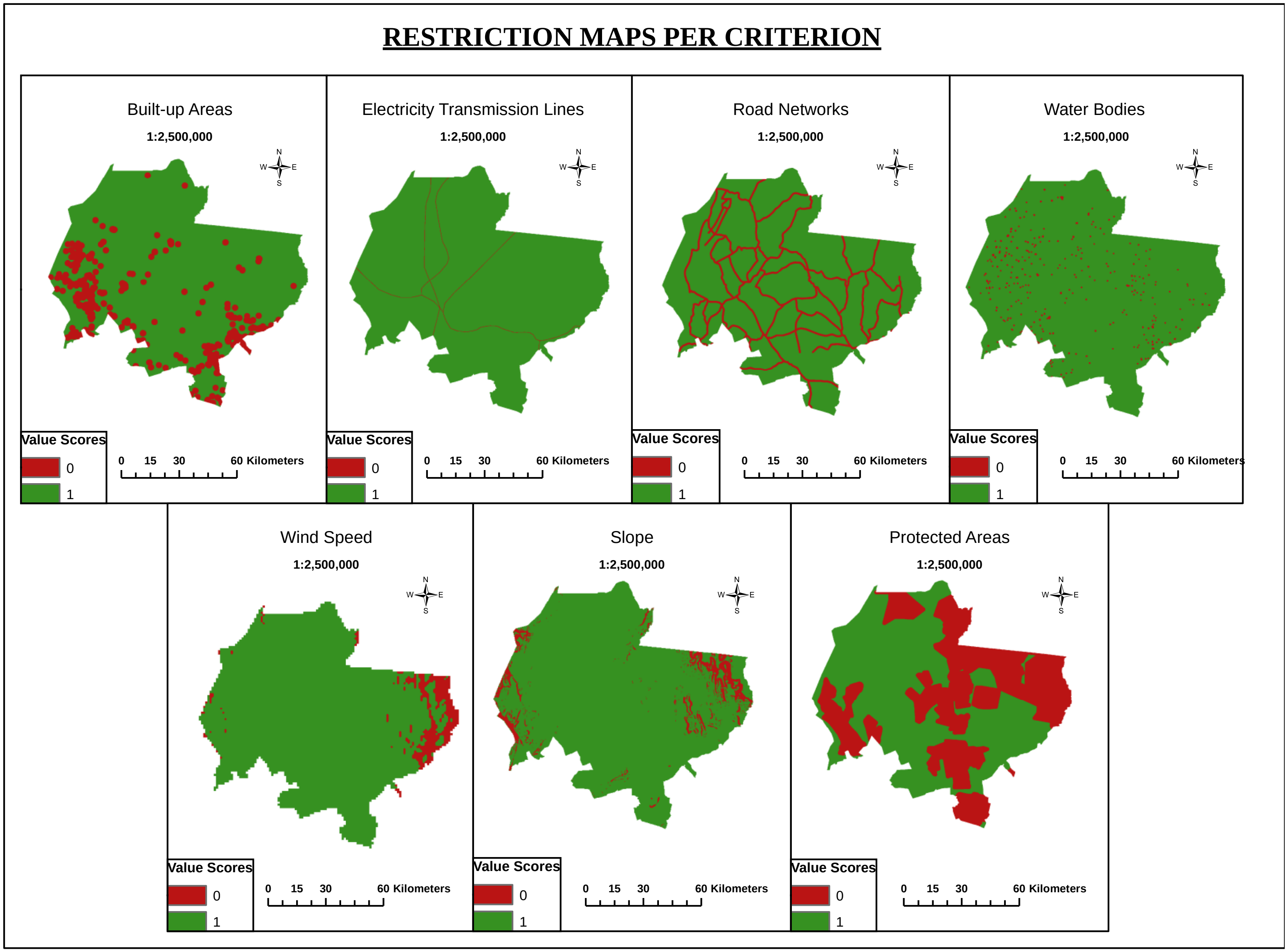

Figure 10: Restriction maps according to each criterion

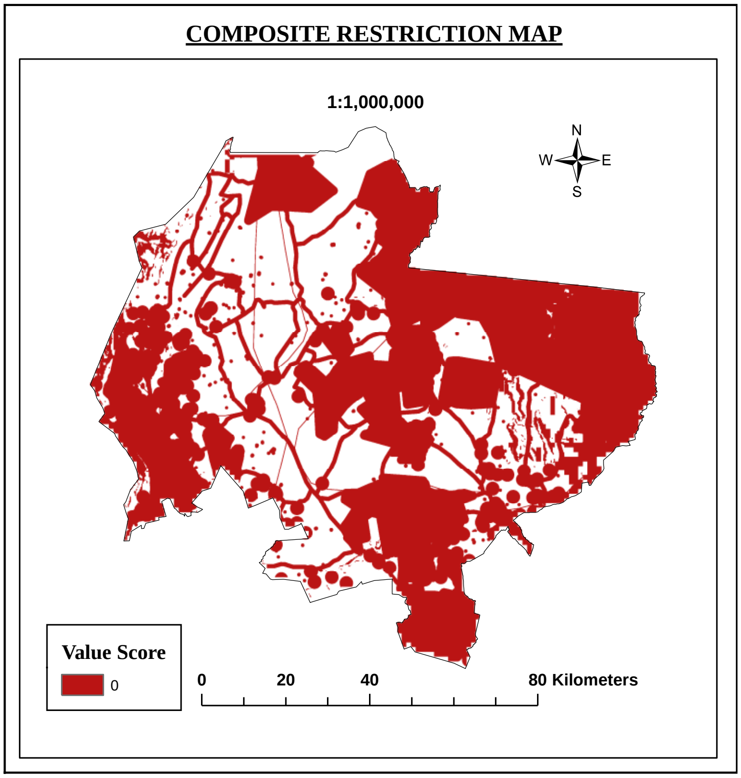

Figure 11: Composite restriction map showing areas excluded from the analysis

Table 8: Approximate area (km^2) and percentages of exclusion zones with respect to the total study area.

Decision Constraint	**Approximate area of exclusion Zones (Km)^2**	**Approximate Percentage of Total Study Area (%)**
Built-up Areas	1577	16.48
Electricity Transmission Lines	71	0.75
Road Network	1221	12.77
Water Bodies	198	2.07
Wind Speed	569	5.95
Slope	563	5.89
Protected Areas	4397	45.96
Combined Restriction	**6010**	**62.83**

Figure 12 presents the individual rated area maps based on selected criteria, with suitability values ranging between one (1), not suitable locations, and ten (10), ideal locations. Figure 13, on the other hand presents the composite rated area map.

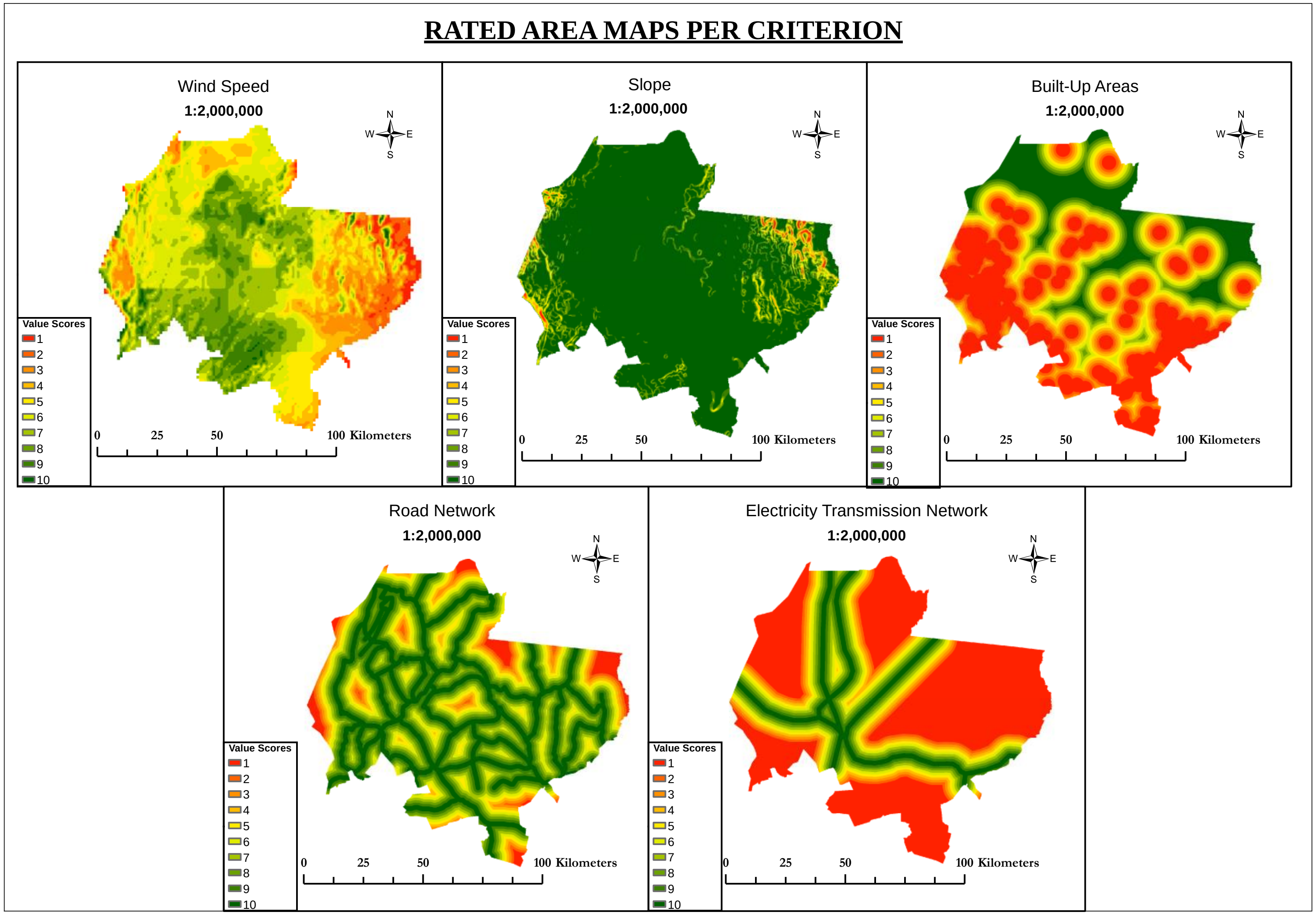

Figure 12: Rated area maps according to each criterion

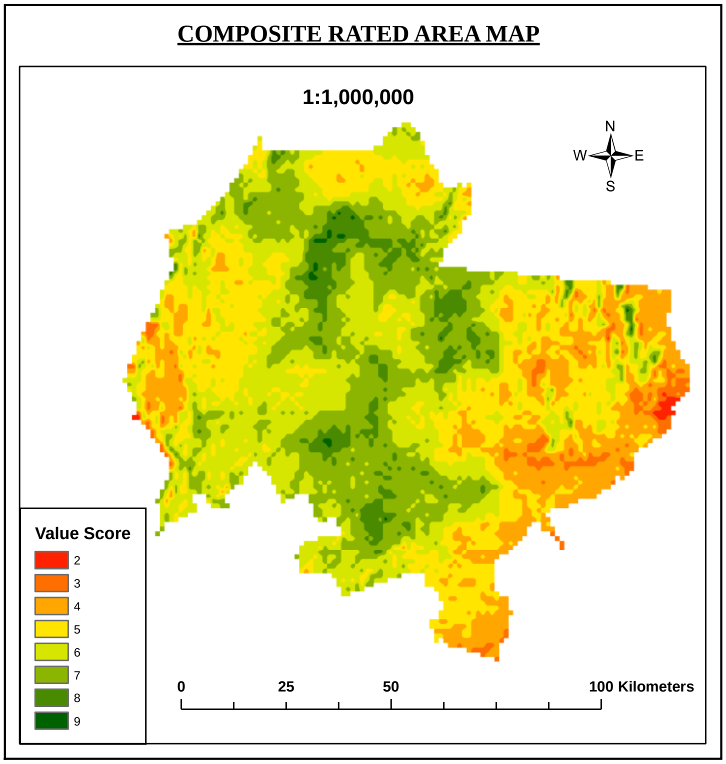

Figure 13: Composite Rated area map

The reclassified suitability map with detailed priority areas are presented in Figure *14*. Priority areas are also listed in Table 9, which shows the percentage of land with 'high suitability', 'medium suitability' and 'low suitability' in relation to the total administrative area. Figure 15 further illustrates the optimal sites for wind farm development based on the defined threshold of 5000 acres.

Table 9: Approximate area (km^2) and percentages of priority areas with respect to the total study area

Priority Area	**Approximate area of Priority Area ($Km)^2$**	**Approximate Percentage of total Study Area (%)**
High Suitability	310	3.04
Medium Suitability	2972	31.07
Low Suitability	291	3.24

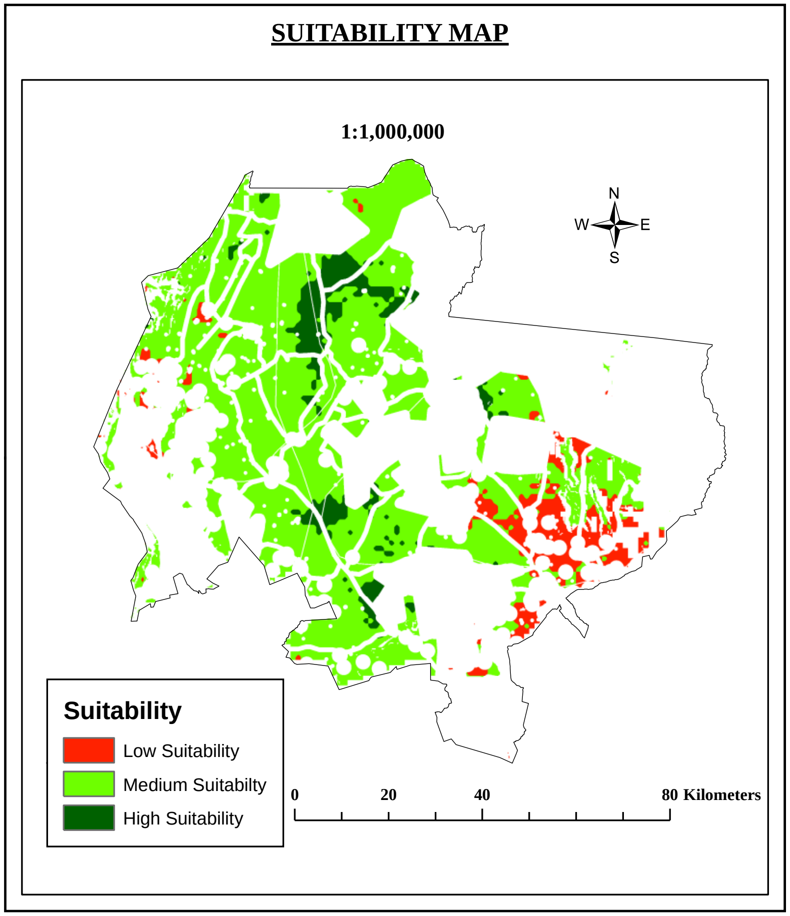

Figure 14: Suitability map for wind farm development

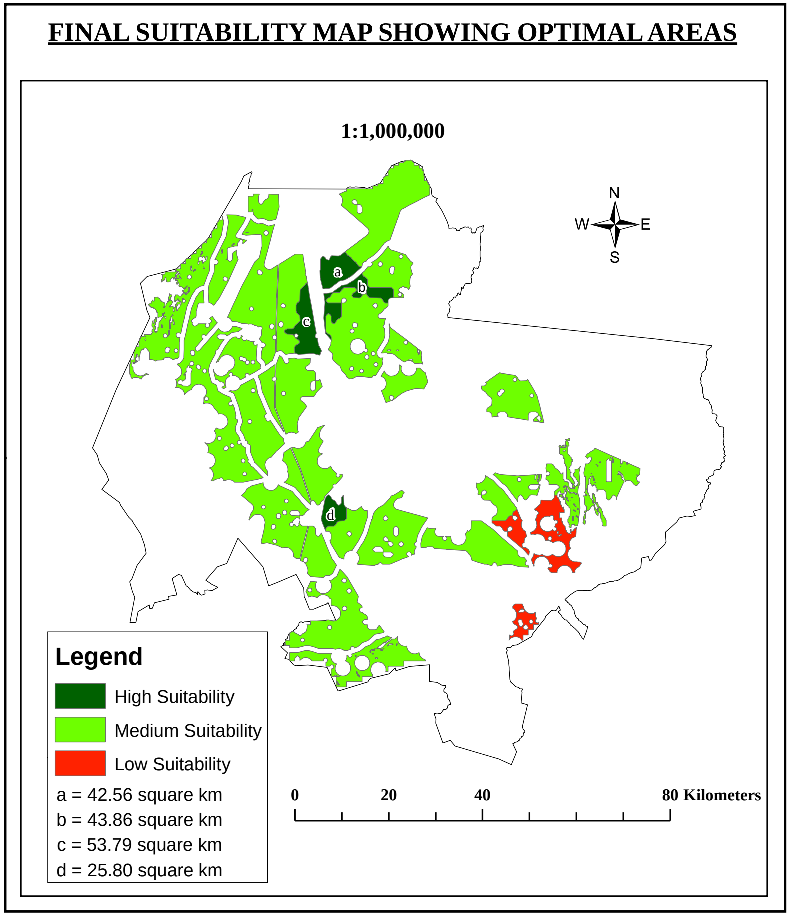

Figure 15: Map showing optimal sites for wind farm development

4.2 Discussion

The extent of the composite restriction layer in this study accounts for approximately 37.2 percent of the entire study area, and thus indicates potential development sites (feasible areas) across Laikipia County. As shown in Figure 10, the spatial extent of the individual decision constraints varies, with protected areas demonstrating the greatest area of exclusion zones, corresponding to approximately 45.96 percent of the entire study area.

Regarding the type of excluded land, most of the areas are excluded due to legal regulations concerning built-up areas and the buffer distances around them, road networks and the buffer distances around them and protected areas. Figure 10 shows that most areas in Laikipia North sub-county and some parts of Laikipia East and West sub-counties are excluded due to environmental regulations, whereas some parts of Laikipia East and West sub-counties are excluded due to their proximity to built-up areas.

As the wind energy potential criterion was rated as the most important criterion, areas with the lowest overall value scores in the overall rated area map were also those with lower scores in the wind energy potential criterion. The wind speed, however, seems to be related to the type of land cover and the slope of terrain. Forested areas and steep slopes tend to have lower wind speeds compared to plane areas. In our analysis, this correlation is particularly prominent in some parts of Laikipia North and West sub-counties around Dol-Dol and Karaba towns respectively, where steep slopes and tree cover causes the lowest wind speed in the region (See also Figure 5).

Areas in and around the protected areas are rated poorly because they get low value scores from three important criteria. Firstly, it is widely accepted that the flora and fauna in these areas have to be protected and that a safe distance has to be kept to protect wind energy-sensitive birds. Secondly, these areas are mostly forested, which is associated with a low value score in the land cover criterion. Lastly, wind speed tends to be lower in the forested areas, which goes along with a low score in the wind energy potential criterion.

Overall, the Central Part of Laikipia seems, without consideration of restricted areas, to be more suitable for the development of wind energy. The main reasons are the high wind energy potential and less protected areas compared to the other regions, high infrastructure accessibility, and the prevalent land cover. In contrast, the extreme Eastern and Western parts of the region are characterized by many protected areas and forested areas and are rated as less suitable.

According to the results obtained, the largest share of areas with high suitability is located around Sosian town in Laikipia North sub-county. This result agrees with the findings of the Energy Regulatory Commission, identifying potential sites for wind farm development in Laikipia North subcounty. The area was found to be of high suitability due to the fact that built-up areas and protected areas are farther away in this area and that the average wind speed is relatively high. Additionally, most areas with high suitability are located on cropland.

The interaction of these beneficial conditions leads to the result that suitable areas in Laikipia can be classified as being of either, high, medium or low suitability. Areas with high and medium suitability in Laikipia East and West sub-counties differ from those in Laikipia North sub-county in that they are surrounded by reserves and are located around forested areas. However, such areas, even though they are close to natural reserves, get higher value scores. Furthermore, only few settlements are located in the proximity. In Laikipia East and West sub-counties, suitable sites are not so large in terms of areal extent and are mostly comprised of medium suitability areas. This might largely be ascribed to the proximity to the natural environments, built-up areas, or both.

5. CONCLUSION AND RECOMMENDATIONS

5.1 Conclusions

The aim of this project was to develop a GIS-based multi-criteria approach to identify the most potentially suitable locations for wind farm developments in Laikipia County. This has been achieved and it is concluded that:

- The developed decision support tool allows for identification of priority areas, as well as optimal areas for development of wind farms.

- Areas around Sosian and Matigari towns in Laikipia North West sub-counties respectively were recognized as high suitability areas and should be of particular interest for further detailed evaluation.

- Majority of the areas with high suitability are located in Laikipia North sub-county, which corresponds to the findings of the Energy Regulatory Commission, during the development of Kenya’s wind energy prospectus. The medium and lower-rated areas were mostly found to be located in Laikipia East and West sub-counties.

- Approximately 3.24 % of the total area of Laikipia County was characterized by high suitability, 31.07% by medium suitability and 3.04% by low suitability.

- The siting procedure proposed in this study can make a contribution can help communities and wind energy planners to identify the most suitable sites for wind energy development, as it provides a comprehensive pre-assessment tool, which allows for a more differentiated evaluation of potential locations in the early stages of planning.

5.2 Recommendations

Future research to improve the accuracy and functionality of the wind farm site suitability map could build on the following recommendations:

- Ground assessment of wind speeds be taken at hub heights at the selected sites to ascertain the wind speeds over a period of time because any margin of error in the calculations and the dataset can make a big difference on the ground.

- Wind data that includes direction be incorporated to determine the most efficient way of orienting the individual turbines on the site.

- The errors from this dataset could have propagated through the analysis and, combined with errors from other layers, may have caused inaccuracies in the output map. Future work will therefore need to investigate the sensitivity of results.

- A follow up study can be conducted to find community response to any potential wind installation on their land.

- A visibility analysis would be a useful add-on to the proposed model to investigate the visual impact of wind farms with respect to the number of visible turbines in relation to their distance.

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Appendix A: **Pairwise Comparison for each criterion (Expert 1)**

Criteria		1	2	3	4	5	6
1	Wind Speed	1	7	7	9	5	5
2	Distance from Transmission Network	0.14	1	0.33	1	0.33	0.33
3	Slope	0.14	3	1	5	0.25	1
4	Distance from Road Networks	0.11	1	0.20	1	0.20	0.33
5	Distance from Built-up Areas	0.20	3	4	5	1	2
6	Landcover	0.20	3	1	3	0.50	1

Appendix B: Pairwise Comparison for each criterion (Expert 2)

Criteria		1	2	3	4	5	6
1	Wind Speed	1	9	9	9	3	7
2	Distance from Transmission Network	0.11	1	1	2	0.17	0.20
3	Slope	0.11	1	1	5	0.25	0.50
4	Distance from Road Networks	0.11	0.50	0.20	1	0.20	0.20
5	Distance from Built-up Areas	0.33	6	4	5	1	3
6	Landcover	0.14	5	2	5	0.33	1

Appendix C: Normalization, average/weights, and consistency (Expert 1)

Criteria		1	2	3	4	5	6	Average	Consistency
1	Wind Speed	0.5587	0.3889	0.5174	0.3750	0.6868	0.5176	0.5074	0.0586
2	Distance from Transmission Network	0.0782	0.0556	0.0244	0.0417	0.0453	0.0342	0.0466	
3	Slope	0.0782	0.1667	0.0739	0.2083	0.0343	0.1035	0.1108	
4	Distance from Road Networks	0.0615	0.0556	0.0148	0.0417	0.0275	0.0342	0.0392	
5	Distance from Built-up Areas	0.1117	0.1667	0.2956	0.2083	0.1374	0.2070	0.1878	
6	Landcover	0.1117	0.1667	0.0739	0.1250	0.0687	0.1035	0.1083	

Appendix D: Normalization, average/weights, and consistency (Expert 2)

Criteria		1	2	3	4	5	6	Average	Consistency
1	Wind Speed	0.5556	0.4000	0.5233	0.3333	0.6061	0.5882	0.5011	0.0729
2	Distance from Transmission Network	0.0611	0.0444	0.0581	0.0741	0.0343	0.0168	0.0482	
3	Slope	0.0611	0.0444	0.0581	0.1852	0.0505	0.0420	0.0736	
4	Distance from Road Networks	0.0611	0.0222	0.0116	0.0370	0.0404	0.0168	0.0315	
5	Distance from Built-up Areas	0.1833	0.2667	0.2326	0.1852	0.2020	0.2521	0.2203	
6	Landcover	0.0778	0.2222	0.1163	0.1852	0.0667	0.0840	0.1254	

Appendix E: Restriction Model

Appendix F: Suitability Model

Appendix G: Final Suitability Model