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Renewable Energy Zones for the Africa Clean Energy Corridor

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RENEWABLE ENERGY ZONES
FOR THE AFRICA CLEAN ENERGY CORRIDOR

MULTI-CRITERIA ANALYSIS
FOR PLANNING RENEWABLE
ENERGY DEPLOYMENT

OCTOBER 2015

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RENEWABLE ENERGY ZONES FOR THE AFRICA CLEAN ENERGY CORRIDOR

Multi-criteria Analysis for Planning Renewable Energy

The International Renewable Energy Agency and
Lawrence Berkeley National Laboratory

OCTOBER 2015

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ACRONYMS AND ABBREVIATIONS

ACEC	Africa Clean Energy Corridor
AICD	Africa Infrastructure Country Diagnostic
CBI	Cross-border Information
DEA	Department of Environmental Affairs (South Africa)
EAPP	Eastern Africa Power Pool
EDM	Electricidade de Moçambique
EEPCO	Ethiopian Electric Power Corporation
ESCOM	Electricity Supply Corporation of Malawi Limited
IEC	International Electrotechnical Commission (publishes wind turbine standards)
IRENA	International Renewable Energy Agency
KETRACO	Kenya Electricity Transmission Co. Ltd
LBNL	Lawrence Berkeley National Laboratory
REDCL	Rwanda Energy Development Corporation, Ltd.
SAPP	Southern African Power Pool
SWERA	Solar and Wind Energy Resource Assessment (United States Agency for International Development)
TANESCO	Tanzania Electricity Supply Company Limited
UETCL	Uganda Electricity Transmission Company Limited
UNEP	United Nations Environment Programme
WDPA	World Database of Protected Areas
ZESCO	Zambia Electricity Supply Corporation Limited
ZETDC	Zimbabwe Electricity Transmission and Distribution Company

DEFINITIONS

Capacity value	The contribution that a given generator makes to overall system adequacy, as determined by profile of system load. It can be defined as the amount of additional load that can be served due to the addition of the generator while maintaining the existing levels of reliability [Keane et al., 2011]
Concentrating solar power (CSP)	Concentrating solar power or solar thermal electricity includes technologies that use mirrors or lenses to concentrate sunlight onto receivers that convert solar energy into heat, and drive steam turbines or heat engines to generate electricity
Direct Normal Irradiance (DNI)	The amount of solar energy per unit area from the direction of the sun, i.e. solar radiation received by a surface that is always held perpendicular to the rays of the sun. Solar DNI is the solar resource used to determine the quality of the solar CSP resource [W/m^2]. This metric is also commonly expressed as insolation in units of kWh/m2day
Effective load carrying capacity (ELCC)	The additional load that a megawatt of a generator at a particular site can support to maintain the same level of system reliability. It is a metric of capacity value.
Geospatial information	Information with indication of physical location in the form of a vector or raster (grid) with spatial reference, or geographic coordinates of location or extent
Global Horizontal Irradiance (GHI)	The amount of solar radiation received by a surface that is horizontal to the ground. Solar GHI is the solar resource used to determine the quality of the solar PV resource [W/m^2]. This metric is also commonly expressed as insolation in units of kWh/m2day.
Geospatial Information System (GIS)	A computer system for capturing, storing, visualizing, and analyzing data related to positions on the earth's surface, and enables to understand relationships, patterns, and trends.
Land use discount factor	Percentage of total potential land (or energy projects) likely developed given additional socio-economic, cultural, or physical constraints identifiable only with higher resolution data or through on-the-ground surveys.
Levelized Cost of Electricity (LCOE)	A metric that describes the average cost of generating electricity at the point of connection to a load or electricity grid for every unit of electricity generated over the lifetime of a project. It includes the initial capital, discount rate, as well as the costs of continuous operation, fuel, and maintenance.
Land use factor	Installable capacity of power generation per unit of land [MW/km^2].
Land Use Land Cover (LULC)	Geospatial data that is a result of classifying raw satellite data into categories of land use (e.g. agriculture, urban build out) and land cover (e.g. forests, snow, wetlands).
MCDA	Multi-criteria decision analysis. This is process by which multiple criteria are considered and weighted by stakeholders.
Photovoltaic (PV)	Photo-voltaic technologies generate electricity directly from sunlight using semiconductor materials.
Project Opportunity Area (POA)	A spatial unit of analysis used in this study.
Renewable Energy	Energy that comes from resources that are naturally replenished on a human timescale such as sunlight, wind, biomass, and geothermal.
Renewable Energy Zone	Contiguous or semi-contiguous area of high potential renewable energy with enough generation capacity to warrant the construction of high voltage (>132 kV) interconnection line. Renewable energy zones typically are created on the basis of within-zone similarity in cumulative suitability scores.
Solar multiple	The ratio of the actual size of the power plant's solar field to the size of the solar field that would be required to drive the turbine at its nominal design capacity assuming standard solar irradiance of 1 kW per m2 at standard temperature and pressure
Utility-scale	Grid connected generation, typically >10 MW

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ERRATUM

RENEWABLE ENERGY ZONES FOR THE AFRICA CLEAN ENERGY CORRIDOR

Grace C. Wu, Ranjit Deshmukh, Kudakwashe Ndhlukula, Tijana Radojicic, Jessica Reilly. (2015) "Renewable Energy Zones for the Africa Clean Energy Corridor," International Renewable Energy Agency and Lawrence Berkeley National Laboratory, LBNL (LBNL-187271).

In the original version of this report (published October 2015), the estimates of capacity value ratios and adjusted capacity factors shown in Figures 23-25 have errors. Originally, capacity value ratios were calculated without correcting for time zone offsets in the wind speed data. The wind speed datasets have now been shifted for each country based on their time zones. Maps in Figures 23-25 showing capacity value ratios and capacity values have been updated in the current version of the report to reflect these corrections. Written content in section 3.2.1 explaining patterns in Figures 23-25 has been updated to reflect these corrections. Specifically, "Mozambique" and "Botswana" were removed from the fourth sentence in the second paragraph and replaced with "Swaziland" and "Ethiopia." Additionally, "southern Namibia" was replaced with "Namibia", "southern Kenya" was replaced with "eastern Kenya", "northern Egypt" was added, and "eastern Botswana" was removed from the last sentence of the third paragraph. In the original version of the report published, Figure 34 was a duplicate of Figure 33. Figure 34 has been replaced with the map that correctly corresponds to the figure caption.

EXECUTIVE SUMMARY

MOTIVATION AND OBJECTIVES

With an average annual gross domestic product (GDP) growth rate of over five percent[1], rapidly developing African countries are well poised to triple their energy consumption in the next few decades. By some estimates, the electricity demand in the countries of the Eastern Africa Power Pool (EAPP) and Southern African Power Pool (SAPP) will collectively exceed 1000 terawatt-hours by 2030, which is more than double the region's electricity consumption in 2010.[2] [3] To achieve this growth via a low-carbon pathway, large-scale renewable energy must form a significant share of the overall generation mix. This study sought to identify and comprehensively value high-quality wind, solar photovoltaic (PV), and concentrating solar power (CSP) resources in 21 countries in the EAPP and SAPP, to support the prioritization of areas for development through a multi-criteria planning process. In order to identify opportunities and challenges for wind and solar development in different regions of the power pools, this study also examined the spatial interactions and patterns of multiple siting criteria.

Inadequate geospatial and economic information regarding renewable energy resources is a significant barrier to policymakers and project developers in promoting socially equitable, low-environmental-impact, and cost-effective development of wind and solar generation technologies in Africa. About half the countries in this study lack even basic renewable energy resource assessments. The ability to identify priority, low-regret renewable energy development options that satisfy multiple stakeholder concerns is crucial for African countries with limited financial and institutional resources for energy planning and development.

In addition to the appropriate economic valuation of high-quality renewable resources, other criteria such as grid operability (temporal correlation between electricity generation and system demand at a particular site), transmission and road infrastructure cost, proximity or overlap with environmentally sensitive areas, and population density are crucial for policymakers, project developers, and other interest groups to make balanced decisions on large-scale renewable energy development. Stakeholders have different objectives and values for these various economic, physical, and socio-environmental criteria. While resource mapping studies in some countries provide a high level perspective of locations of high-quality resource areas, most studies of African countries are static and lack the ability to allow stakeholders to select their own criteria and weights in order to prioritize high-quality renewable energy areas for development.

THE MULTI-CRITERIA ANALYSIS FOR PLANNING RENEWABLE ENERGY METHODOLOGY

Multi-criteria Analysis for Planning Renewable Energy (MapRE) is a study approach developed by the Lawrence Berkeley National Laboratory with the support of the International Renewable Energy Agency (IRENA). The approach combines geospatial, statistical, energy engineering, and economic methods to comprehensively identify and value high-quality wind, solar PV, and solar CSP resources for grid integration based on techno-economic criteria, generation profiles (for wind), and socio-environmental impacts. The ACEC renewable energy zones study included the following 21 countries in the EAPP and SAPP: Angola, Botswana, Burundi, Djibouti, Democratic Republic of Congo, Egypt, Ethiopia, Kenya, Lesotho, Libya, Malawi, Mozambique, Namibia, Rwanda, South Africa, Sudan, Swaziland, Tanzania, Uganda, Zambia, and Zimbabwe. Energy engineering analyses used best available empirical values for

[1] The World Bank, 2014. "Africa's growth set to reach 5.2 percent in 2014 with strong investment growth and household spending," Press release.

[2] Eastern Africa Power Pool, 2011. "Regional power system master plan and grid code study."

[3] Southern African Power Pool, 2007. "SAPP regional generation and transmission expansion plan study."

estimating wind capacity factors that account for air density variation across different elevations and temperature and optimal turbine selection based on the average wind speed. We used industry-standard models and regression analysis to estimate capacity factors for solar CSP with 6 hour thermal storage. We employed statistical clustering methods to identify large areas of potential, or zones, by minimizing the variance of the resource quality within zones while maintaining spatial contiguity. For each zone, we estimated various criteria relevant to prioritizing and valuing potential renewable energy projects. These included levelized cost of electricity (LCOE) of generation, LCOE of transmission and road infrastructure, the capacity value of generation, distance to nearest significant load center, distance to nearest planned or operational geothermal power plant, distance to nearest planned or operational wind or solar plant, the overlap with suitability for other renewable technologies, distance to nearest surface water source, population density, human footprint score, land use and land cover, and slope.

In order to estimate distances and electricity costs, we gathered spatial data from each country on locations and voltages of transmission lines and substations, load centers, and planned or operational renewable power plants. In addition, we solicited at least one year's worth of hourly electricity demand data for each country. Using these and simulated hourly wind generation estimates from 3Tier Inc. (now Vaisala Inc.), we estimated the capacity value of 400 select wind locations across the study region to assist in identifying the zones with generation profiles that best contribute to meeting each country or region's peak demand. This systematic quantification of a potential renewable energy site's contribution towards grid reliability and its comparison with other siting criteria is one of the first of its kind for any country within our study region.

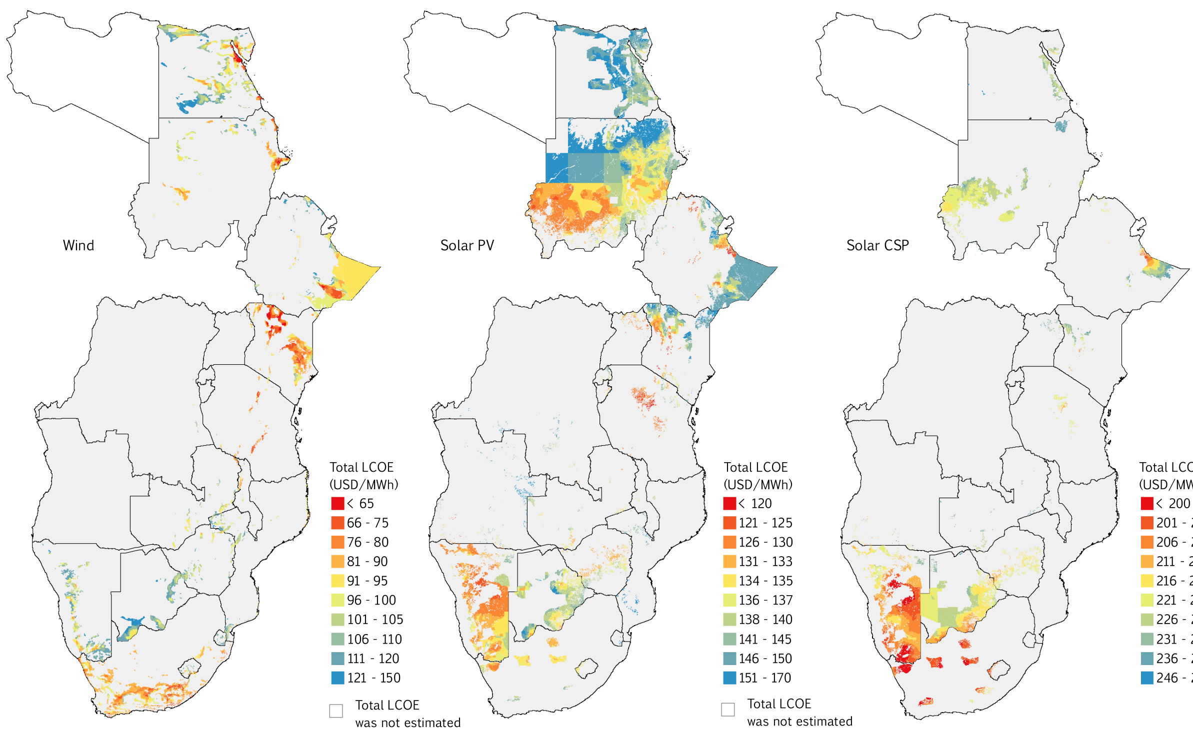


FIGURE 1: Average total levelized cost of electricity (LCOE) of wind (A), solar PV (B), and solar CSP (C) zones estimated using resource quality, distance to the nearest transmission line or substation, and distance to the nearest road.

KEY FINDINGS

Although abundant wind, solar PV, and solar CSP resources exist within the EAPP and SAPP, the uneven geographic distribution of high-quality resources demonstrates that regional collaboration and grid interconnection will be necessary to promote the supply of low-cost clean wind and solar energy to all countries. Angola, DRC, Rwanda, and Burundi lack cost-effective wind zones, but they can benefit from the high-quality wind resources in their neighboring countries, Tanzania, Zambia, and Namibia. In the case of solar PV, it may be more cost-effective for countries such as Rwanda and Swaziland with lower quality PV potential to import solar PV electricity from Tanzania and South Africa, respectively. **Regional grid interconnection will enable countries to share other renewable resources such as geothermal, as well as conventional resources such as hydro, for balancing the variability of wind and solar generation.** With increasing wind and solar electricity, existing hydro generation in countries such as Ethiopia, Mozambique, DRC, Uganda, Zambia and Malawi could provide balancing services to regional grids. At the same time, solar and wind generation may reduce the risk of inter-annual and climate-driven variation of hydropower resource availability.

Agricultural land will be important for wind development in particular countries where dual land use strategies could help to spur wind development while supporting farmers economically. Agricultural land comprises about half the wind resource area in Malawi, Mozambique, Tanzania, and Zimbabwe, and greater than half in Zambia. In anticipation of possible land use conflict, policy makers in these countries should pursue land use policies such as land leasing to ensure equitable development that balances multiple uses.

Consideration of wind capacity values using annual peak demand hours substantially increases the geographic distribution and abundance of favorable wind zones, compared to a case that considers only annual average capacity factors. It is crucial to incorporate capacity value, which is a measure for how well generation temporally matches peak demand, in prioritizing wind zones because variable renewable zones with higher capacity values (capacity factors estimated during the peak demand hours within a year) will result in larger offsets in conventional generation capacity. In ACEC, many zones with low annual average capacity factors (<30% CF) show capacity values that are comparable and competitive with the high annual average capacity factor zones (>40% CF). Importantly, consideration of wind capacity values increases the number of favorable zones across the ACEC. Moreover, most of the wind zones in countries such as Zambia, Zimbabwe, Mozambique and Tanzania that have lower wind potential, have high capacity value. Finally, many of these high capacity value wind zones are closer in proximity to load centers than zones with high annual average capacity factors.

Almost all countries with sufficient renewable energy potential can develop zones that are cost-effective and have low environmental impact. Many of these zones are also close to existing transmission infrastructure and major load centers, thus requiring lower transmission extension and upgrade costs and lower transmission-associated land use. However, because high-quality, abundant resources also exist in areas that are relatively ecologically intact, development of these zones must be actively avoided through pre-emptive land use and electricity policies that promote low impact development. Additionally, the consideration of capacity value of wind zones as well as LCOE increases the overall suitability of zones that are close to transmission infrastructure, load centers, and have lower environmental impact.

Many wind zones throughout the corridor are also suitable for the development of solar PV, which suggests that co-location could be an important siting strategy to maximize transmission capacity utility, minimize land use, and increase return on investment. In zones suitable for both wind and solar PV development, the space between turbines on a wind farm could be filled with solar PV arrays, with only 1-2% generation loss due to turbine shading. Land and other ancillary infrastructure project costs can be shared between the two generation technologies, which reduces the overall project cost and development risk, particularly for zones further from existing transmission infrastructure.

Renewable energy planning using a multi-criteria approach promotes more socially and environmentally equitable, cost-effective, and reliable generation development. The ACEC renewable energy zones study is the first to conduct detailed multi-criteria wind and solar zoning analysis for the Southern and Eastern Africa Power Pools. The results of this study demonstrate that the best zones for development significantly differ depending on the criteria considered. Stakeholders can use the renewable energy zones interactive map and zone ranking tools, which integrate the results of this study, to determine whether zones have complementary or conflicting siting criteria and to select zones that best resolve conflicts. The feedback and expressed input of stakeholders in multiple stages throughout the process of this study explicitly guided the development of the tool for immediate implementation throughout the region.

Modelling and analysis can only be expeditiously and accurately conducted if government agencies and utilities collect, maintain, and share data. Due to the size of the study region and the integration of multiple project development criteria, this study required an enormous data collection undertaking. The spatial and non-spatial data required to conduct zoning analysis were often not readily available or were maintained in digital formats, such as PDFs, ill-suited for spatial or statistical analysis. Although this study was able to identify wind and solar zones using limited data, this and any future study would benefit from more spatial data, such as that on land ownership, conflict regions, nomadic peoples' land use, ecological value, and wildlife corridors. If countries desire to conduct and use zoning studies in the future to inform the rapid development of wind and solar projects that are cost-effective, as well as socially and environmentally responsible, they will need to actively collect and maintain data to support such studies.

DECISION-MAKING TOOLS

addcontentslinetocsubsection Decision-making tools

To extend the value of these analyses for policymakers, developers, and energy planners, we integrated results into a dynamic **multi-criteria zone ranking tool** that allows users to select and weigh different criteria to create a supply curve that ranks zones according to criteria weights (Figure 2).

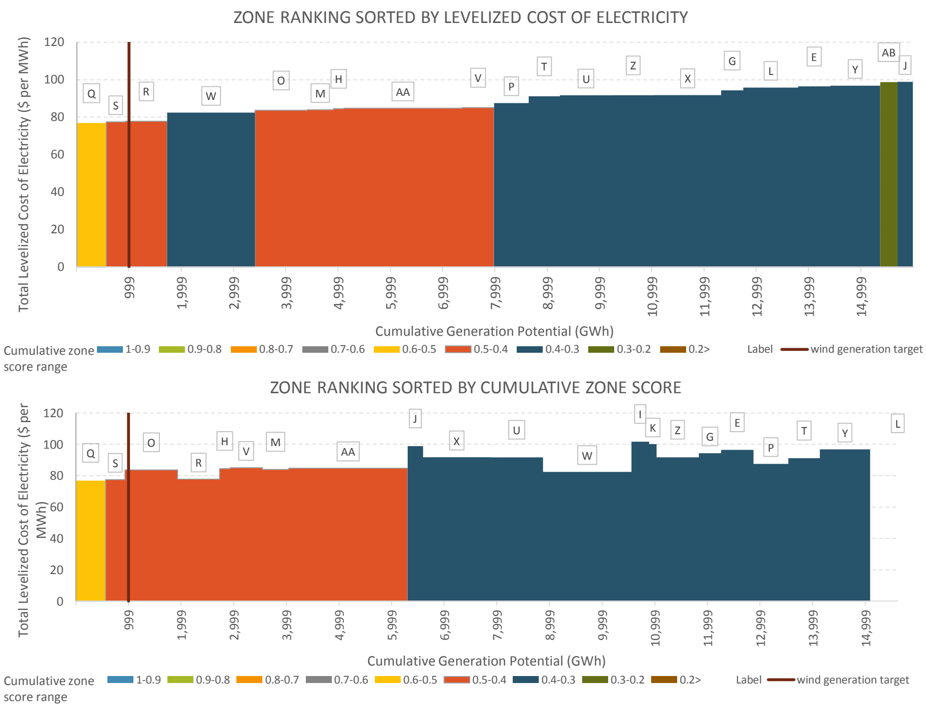


FIGURE 2: Wind energy zone supply curves – an output of the multi-criteria planning tool.

The tool ranks zones by their estimated total levelized cost of electricity (supply curve A) and their zone score (supply curve B), which is dynamically calculated by user defined weights. Zones are color coded by their score bins and can be identified by unique zone ID codes above each bar. Vertical line shows electricity demand in 2030 as a reference for future growth in electricity demand, or a user-specified renewable energy generation target.

We designed the Microsoft Excel-based planning tool (Figure 2) to be used in conjunction with **interactive PDF maps** (Figure 3) created for each country and for each of the two power pools. These georeferenced PDF maps embed both the visual content as well as the criteria attribute values of the key spatial inputs and zones. Users are able to rank zones based on country-specific ranges of scores, or SAPP- and EAPP-wide ranges, which is useful for planning domestic electricity generation or regional interconnections for international electricity markets, respectively. For policymakers, these maps and tools will enable preemptive planning of transmission and other infrastructure that will encourage development by reducing project risk in selected zones. To encourage further research and updates, input and output datasets are available for public download.

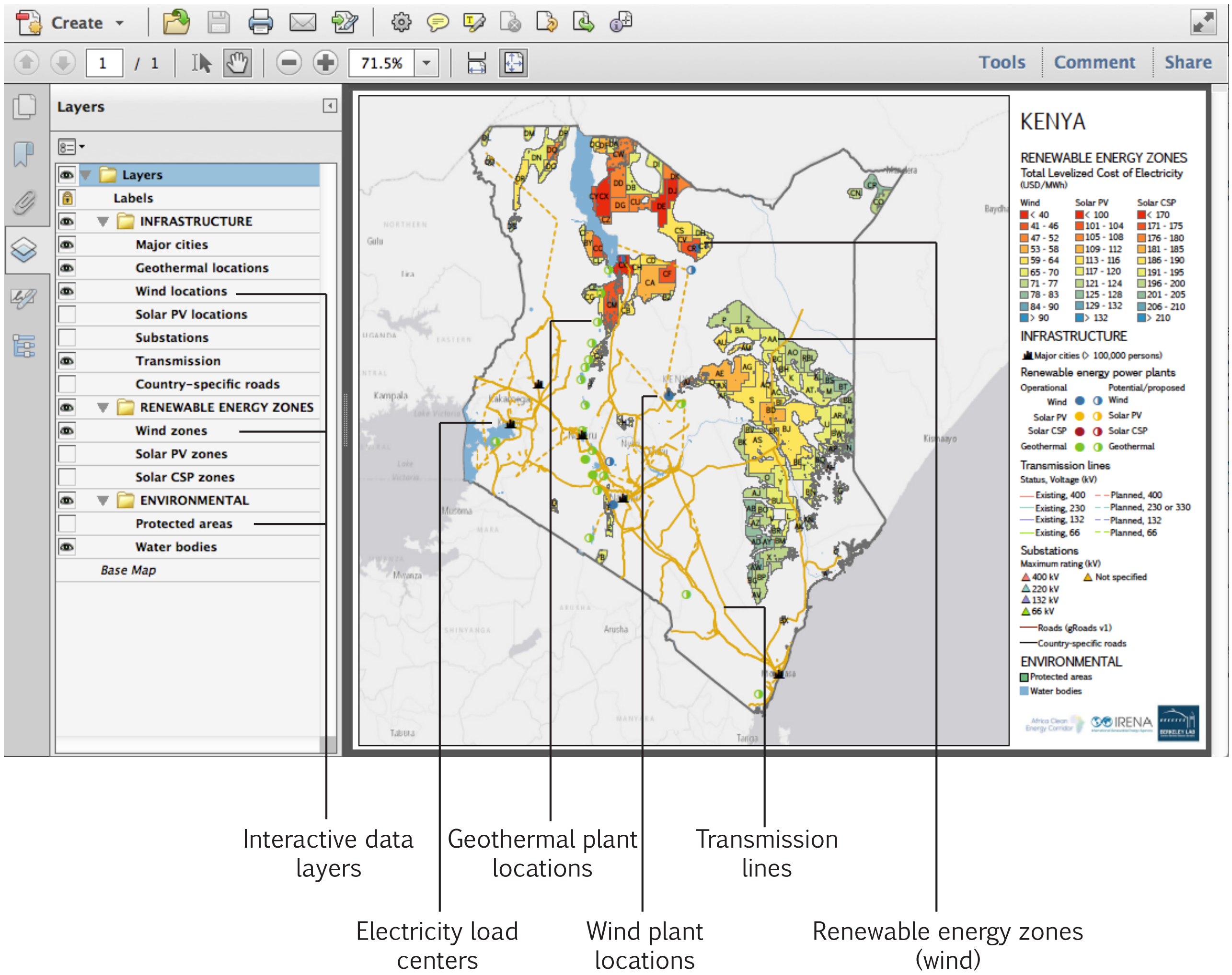


FIGURE 3: Interactive PDF map for Kenya showing wind energy zones and other data inputs.

1 INTRODUCTION

With an average annual gross domestic product (GDP) growth rate of over five percent[4], rapidly developing African countries are well poised to triple their energy consumption in the next few decades. By some estimates, the Eastern Africa Power Pool (EAPP) and Southern African Power Pool (SAPP) electricity demand in 2030 will collectively exceed 1000 TWh, which is more than double the region's electricity consumption in 2010 [EAPP et al., 2011] [SAPP and Nexant, 2007]. Grid-connected renewable energy (RE) generation that include wind, solar photovoltaic (PV), concentrating solar power (CSP), and geothermal can significantly contribute to in meeting this growth in demand.

To achieve this growth via a low-carbon pathway, large-scale renewable energy must form a significant share of the overall generation mix. Identifying renewable energy resource areas with high-quality potential and low environmental and social impacts can enable rapid yet appropriate deployment of renewable power generation plants and expansion of transmission systems.[5] In this study, as part of the Africa Clean Energy Corridor (ACEC) initiative, the Lawrence Berkeley National Laboratory (LBNL) and the International Renewable Energy Agency (IRENA) present the Africa Clean Energy Corridor (ACEC) Renewable Energy Zones study and the LBNL-developed Multi-criteria Analysis for Planning Renewable Energy (MapRE) approach to identify and comprehensively value high-quality wind, solar PV, and solar CSP in order to support prioritization development areas through a multi-criteria planning process.

1.1 AFRICA CLEAN ENERGY CORRIDOR INITIATIVE

The Africa Clean Energy Corridor (ACEC) is an IRENA co-ordinated regional initiative promoting accelerated development of renewable energy potential and cross-border trade of renewable power within the EAPP and SAPP. The initiative assesses cost-effective renewable energy resources; encourages the incorporation of higher shares of renewable energy in generation expansion plans; promotes more coordinated planning of generation and transmission; builds an enabling environment for renewable energy investment; builds regional capacity to plan, construct, operate, and govern power systems with more renewable energy; and raises awareness on the overall benefits of the ACEC [IRENA, 2014]. Hydropower currently dominates large shares of the electricity supply in many African countries. To facilitate the planning of diverse and lower risk clean generation portfolios, this study focuses on emergent renewable energy resources. In this study, we identify wind, solar PV, and solar CSP energy zones, and map pre-identified high-quality geothermal resource areas, to facilitate ACEC transmission planning in 21 member countries in EAPP (Burundi, Djibouti, Democratic Republic of Congo, Egypt, Ethiopia, Kenya, Libya, Rwanda, Sudan, Tanzania and Uganda) and SAPP (Angola, Botswana, Democratic Republic of Congo, Lesotho, Malawi, Mozambique, Namibia, South Africa, Swaziland, Tanzania, Zambia, and Zimbabwe).[6]

High-quality renewable energy resources may be spatially heterogeneous across the ACEC, with some countries having better quality resources than others. Increased interconnections between countries and regions can enable the transmission of electricity across utilities and regional grids from the most cost-effective renew-

[4] The World Bank, 2014. "Africa's growth set to reach 5.2 percent in 2014 with strong investment growth and household spending," Press release.

[5] Although we recognize that decentralized and distributed renewable energy generation can play a significant role in providing access to basic electricity service, in this study, we focus on the development of utility-scale or large-scale wind, solar PV and solar CSP plants that will be connected to the transmission grid.

[6] Democratic Republic of Congo and Tanzania are part of both EAPP and SAPP.

able energy resource areas to the neediest load centers. Further, the transmission infrastructure being planned for other conventional generation sources such as hydropower can be leveraged by renewable energy generators if they are proximally located. Finally, identification of high-quality renewable energy zones can reduce the risk to project developers, utilities, and government agencies by facilitating preemptive transmission planning that encourages socially and environmentally responsible development, thus lowering costs and enabling rapid growth of RE.

1.2 RENEWABLE ENERGY ZONES IN TRANSMISSION PLANNING

The use of multi-criteria decision analysis (MCDA) in conjunction with geographic information systems (GIS) tools to assess energy development potential and inform land use planning processes, for both conventional and renewable energy projects, has a long history. Several academic studies have applied variants of a joint GIS-MCDA methodology to address specific siting challenges and whether certain generation technology-specific policy targets can be met by available land [Stoms et al., 2013] [Kiesecker et al., 2011]. Other studies have examined and refined criteria specific to certain technologies, especially in anticipation of or in reaction to increasing market or government interest in these technologies (e.g., solar CSP). These improvements in suitability models involve inclusion of more relevant siting criteria [Dawson and Schlyter, 2012], or site scores based on ranked or weighted criteria [Janke, 2010]. Most recently, concerns about sustainably meeting projected energy demand on a national or regional scale has prompted analyses that incorporate a broader spectrum of siting criteria, are high-resolution yet large scale, and are multi-technology in scope. One such study is the Oak Ridge Siting Analysis for power Generation Expansion tool (OR-SAGE) developed by the Oak Ridge National Laboratory for the entire continental United States [Omitaomu et al., 2012].

Several significant renewable energy zoning studies for the purposes of transmission planning have been conducted for the United States. The most notable of these include the California Renewable Energy Zones commissioned by the California Public Utilities Commission [CPUC, 2009], the Energy Zones Study for the Eastern Interconnection conducted by Argonne National Laboratory [Argonne National Laboratory et al., 2013], and the Texas Competitive Renewable Energy Zones (CREZs) commissioned by the Public Utility Commission of Texas [ERCOT, 2008]. The first few transmission lines identified and planned through the Texas CREZ project have begun to relieve congestion on the electricity grid, facilitating the transmission of wind power from the northwest areas of the state to the load centers in the southeast [ERCOT, 2008]. While renewable energy potential assessments have been conducted for countries in Africa [Hermann et al., 2014], a South African study is the first in Africa to identify renewable energy development zones in order to streamline environmental impact assessment applications and promote a low-environmental-impact and more equitable siting process for renewable energy [DEA and CSIR, 2014].

1.3 STUDY OBJECTIVES AND APPROACH

1.3.1 OBJECTIVES

The renewable energy zones study, which uses LBNL's Multi-criteria Analysis for Planning Renewable Energy (MapRE) approach aimed to achieve the following objectives:

1. Comprehensively identify and value high-quality wind, solar PV, and solar CSP zones for grid integration based on techno-economic criteria, generation profiles (for wind), and socio-environmental impacts.[7]

2. Map the abundance and quality of wind and solar zones across the potential clean energy corridor for Eastern and Southern Africa.

3. Identify potential siting challenges due to the pre-

[7]Capacity value estimations that use generation profiles were conducted only for wind, and not for solar technologies due to the limitations in the scope of this study.

dominance of particular land use/land cover types within a country.

4. Examine the extent to which capacity value of wind reinforces or changes the distribution of economically valuable wind zones across the corridor.

5. Examine opportunities for cost-effective and low-environmental impact wind and solar development.

6. Identify zones suitable for the development of more than one generation technology as these zones could offer opportunities for co-location.

For the ACEC region, we refer to areas of renewable resource potential as the Southern and Eastern Africa Renewable Energy Zones (SEAREZs). For each zone, we estimated various criteria relevant to prioritizing and valuing potential renewable energy sites (e.g., levelized cost of electricity (LCOE) of generation, LCOE of transmission and road infrastructure, the capacity value of generation, distance to nearest significant load center, human footprint score). By utilizing energy engineering and economics in conjunction with geospatial analysis, we identify high-quality resources that reduce additional transmission and road linkages and minimize socio-environmental impacts. One of the key contributions of this study is a corridor-wide assessment of wind zones' capacity values, a metric that helps identify the zones with generation profiles that best contribute to meeting each country's or region's peak demand. This systematic quantification of a potential renewable energy site's contribution towards grid reliability and its comparison with other siting criteria is one of the first of its kind for any country within our study region.

1.3.2 APPLICATION

In this study, we quantified criteria for each SEAREZ that policymakers, project developers, and other stakeholders may use to prioritize the zones through a stakeholder process. To facilitate this process, we integrated the results into a dynamic, multi-criteria zone ranking tool that allows users to select and weigh different criteria to create a supply curve that ranks zones according to criteria weights. We designed this Microsoft Excel-based planning tool to be used in conjunction with interactive PDF maps created for each country and for each of the two power pools. These georeferenced PDF maps embed both the visual content as well as the criteria attribute values of the key spatial inputs and zones. Users are able to rank zones based on country-specific ranges of scores, or SAPP- and EAPP-wide ranges, which is useful for planning domestic electricity generation or regional interconnections for international electricity markets, respectively. For policymakers, these maps and tools enable preemptive planning of transmission and other infrastructure that will encourage development by reducing project investment risk in selected zones. To encourage further research and updates, input and output datasets are available for public download.

LBNL's Multi-criteria Analysis for Planning Renewable Energy (MapRE) modeling approach is not a static process. This ongoing effort must remain dynamic due to changing physical and socio-political infrastructure and increased access to improved data. Limitations include the discrepancies inherent in meso-scale resource data (which are validated by limited ground-level measurement data), limited spatial data availability, and outdated data. Data gathering is a multi-stakeholder effort that can support capacity building of Africa-based agencies and organizations and ultimately expand the eastern and southern Africa energy data infrastructure along with the physical renewable energy infrastructure. We hope that regional and country agencies adopt and improve upon the data and methods presented in this study to meet their needs and requirements. Planning and developing energy infrastructure is and should be a stakeholder driven process, informed by structured decision-making tools and a development framework.

2 METHODOLOGY

2.1 METHODS OVERVIEW

We applied LBNL's Multi-criteria Analysis for Planning Renewable Energy (MapRE) modeling approach the Africa Clean Energy Corridor (ACEC) Renewable Energy Zones study. This modeling approach uses a framework founded in previous resource assessment and zoning studies, but significantly improved and adapted, particularly to account for data limitations in African countries. The following summary briefly describes the methodology flowchart in Figure 4.

We first conducted a **(1) resource (potential) assessment** using thresholds and exclusion categories to identify all technically viable land for renewable energy (RE) development. Resource quality thresholds (e.g. W/m^2) and other criteria were adjusted (within an economically viable range) in order to identify potential comparable with country demand projections. To **(2) create project opportunity areas**, we divided the resource areas into spatial units of analysis referred to as "project opportunity areas" (POAs) with land area ranges (after applying a land-use discount factor) representative of utility-scale wind and solar power plants. In order to account for the percentage of projects that could realistically be developed in any given area of renewable energy potential, a land use discount factor was applied based on developer experiences reported in previous zoning studies. The choice of POA land areas were not meant to suggest that an entire POA must be developed. To **(3) estimate project opportunity area attributes**, we calculated average values for multiple siting criteria, including distances to existing transmission and road infrastructure. These criteria were then used to estimate each POA's component and total levelized cost of electricity (LCOE) for each technology. Using a statistical regionalization technique, we clustered POAs on the basis of their resource quality (W/m^2) similarity in order to **(4a) create zones** that vary in size from 30 km^2 to 1000 km^2. The actual size were determined by the regionalization algorithm based on the extent of spatial homogeneity in resource quality. In order to **(4b) calculate zone attributes**, we calculated the area-weighted average value of attributes of all POAs within a zone. For wind **(5) capacity value estimates**, 400 locations across the entire study region were selected based on abundance and quality of wind resource and spatial representation across the ACEC. Using 10 years of simulated hourly wind speed profiles from 3Tier (now Vaisala Inc.), a leading long-term renewable resource data provider, for each of 400 locations and hourly demand profiles for each country, we estimated capacity value ratios using the top 10% of annual demand hours and the top three daily demand hours for each of the 400 wind locations. Wind zones were then assigned capacity value ratios using the distance to the nearest location with hourly wind speed data.

For **(6) multi-criteria scoring** of each zone, we assigned every criteria value (e.g., percentage of slope, population density, LCOE, capacity value) a score ranging from 0 (least favorable) and 1 (most favorable) based on the maximum and minimum criteria values within a country and across the ACEC. Users of the **multi-criteria zone ranking tool** are able to assign weights to each criteria in order to calculate and rank cumulative zone scores, visualized using zone supply curves. The ranked zones can be geographically located on the **interactive PDF maps** using each zone's unique zone identification.

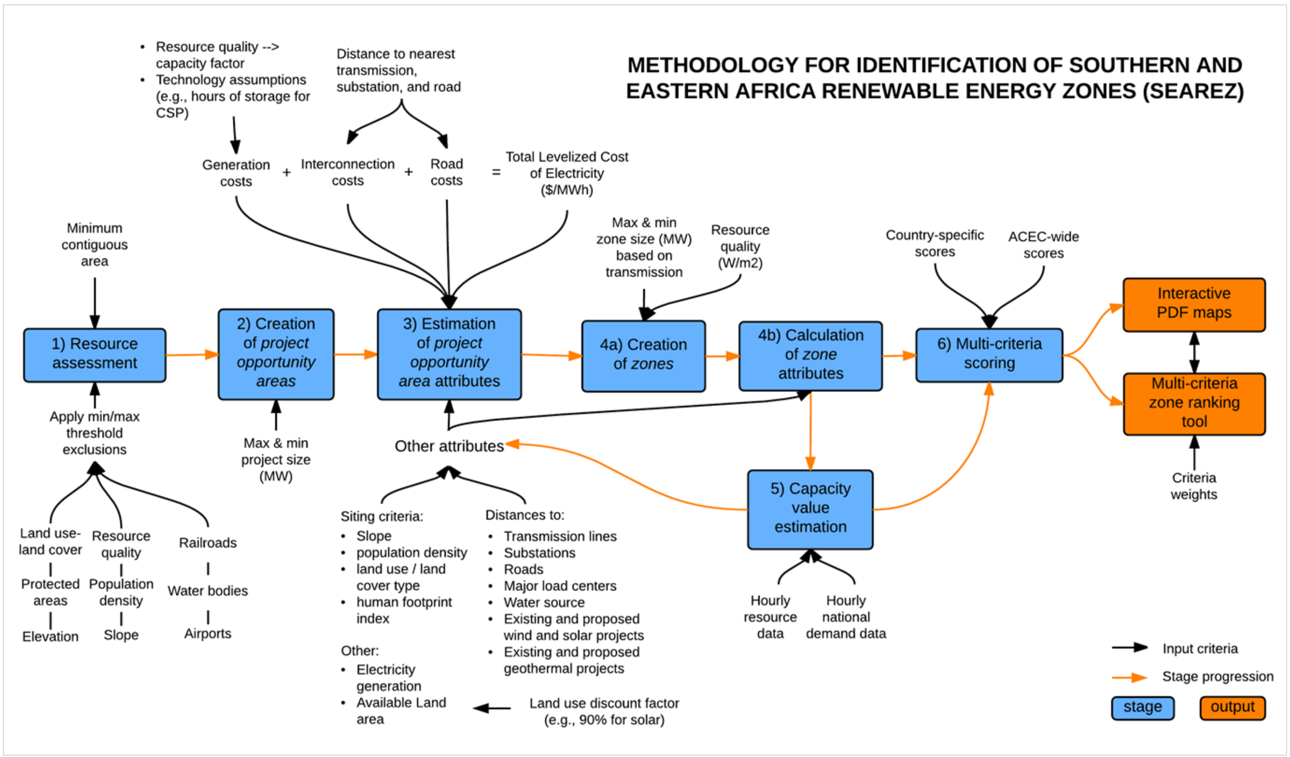


FIGURE 4: Methods flow chart showing the LBNL Multi-criteria Analysis for Planning Renewable Energy (MapRE) model (blue boxes) and the ACEC renewable energy zoning outputs (orange boxes).

2.2 DATA COLLECTION

A comprehensive zoning process requires various types of physical, environmental, economic, and energy data in both specific spatial and non-spatial formats. We rely on a combination of global or continental default spatial data and country-provided datasets. The former serve the purpose of filling in missing country data and provide spatial uniformity for critical physical characteristics (e.g., elevation, wind speed). Country-specific datasets ensure consistency with similar past and ongoing national efforts, and in some cases, greater accuracy. We collected these data for 21 participating countries in the ACEC through a combination of stakeholders and country contacts at government agencies, utilities, and industries. Data availability and sources are tabulated for each country in Appendix A (Table 11 through Table 14). We could not acquire critical data for many countries, particularly up-to-date transmission (or substation) spatial data, hourly demand profiles, and protected areas. The full zoning analysis and ranking could not be completed for Libya and Djibouti since it lacked requisite country-specific datasets.

2.3 RESOURCE ASSESSMENT FOR WIND, SOLAR PV, AND CSP (STAGE 1)

Zoning analysis began with identifying areas that met baseline technical, environmental, economic, and social suitability criteria[8] for renewable energy development. Using default and country-provided data (Table 1), Python programming and the ArcPy library for spatial analysis, we estimated resource potential. Resource potential estimates rely on a linear combination of binary exclusion criteria after applying thresholds for the following data types: techno-economic (elevation, slope, renewable resource quality, water bodies), environmental (land-use/land-cover, protected areas), socio-economic (population density, railroad, airports) (Table 1). Specifications for thresholds and buffer distances for unsuitable areas follow international industry standards. [Black & Veatch Corp. and NREL, 2009] [CPUC, 2009]

[8]Such criteria ensure that renewable energy plants are not built on areas that have high population density, agricultural value, or some level of environmental protection for non-energy resources such as biodiversity or water.

[Lopez et al., 2012] [REEEI and GESTO, 2012] We imposed a minimum contiguous area of 2 km^2 for both wind and solar technologies. The technology-specific land-use/land-cover (LULC) categories are listed in Table 2. All analyses were performed at 500 m resolution using Africa Albers Equal Area Conic projection.

TABLE 1: Default spatial datasets

Stage of analysis	Category	File type	Source	Description	Year	Default exclusion thresholds
Resource assessment	Boundaries	Vector	Global Administrative Database (GADM) v2	GADM is a spatial database of the location of the world's administrative areas (or administrative boundaries) for use in GIS and similar software. Administrative areas in this database are countries and lower level subdivisions.	2012	
Resource assessment	Elevation	Raster	Shuttle Radar Topographic Mission (SRTM) – CGIAR-CGI Digital Elevation dataset v4.1	Produced by NASA originally, the SRTM is a major breakthrough in digital mapping of the world and provides a major advance in the accessibility of high-quality elevation data for large portions of the tropics and other areas of the developing world. 3 arc seconds (approx. 90 m) resolution.	2000	>1500 m (all technologies)
Resource assessment	Slope	Raster	SRTM - CGIAR	Created from elevation dataset using ArcGIS 10.2 Spatial Analyst.	2000	>5% (solar); >20% (wind)
Estimation of Project opportunity area attributes	Temperature	Raster	WorldClim	WorldClim is a set of global climate layers (climate grids) with a spatial resolution of about 1 square kilometer. Hijmans, R.J., S.E. Cameron, J.L. Parra, P.G. Jones and A. Jarvis, 2005. Very high-resolution interpolated climate surfaces for global land areas. International Journal of Climatology 25: 1965-1978. http://www.worldclim.org/formats	1950 - 2000	
Resource assessment	Land use/land cover (LULC)	geotiff	ISGCM - Global Map V.2 (Global Version)	The Global Land Cover by National Mapping Organizations (GLCNMO) is the data of 500m (15 arc seconds) grid with 20 land cover items. The data were created by using MODIS data observed in 2008 (Terra & Aqua Satellites) with the cooperation of NMOs of the world in providing training data and validation. The classification is based on LCCS developed by FAO.	2008	See Table 2
Resource assessment and Project opportunity area attributes	Water bodies	.shp	World Wildlife Federation Global lakes and wetlands database	Comprises lakes, reservoirs, rivers and different wetland types in the form of a global raster map at 30-second resolution. We excluded the following categories: lake, reservoir, river, freshwater marsh, floodplain, swamp forest, flooded forest, coastal wetland, brackish/saline wetland, and intermittent wetland/lake from. www.worldwildlife.org/pages/global-lakes-and-wetlands-database	2004	<500 m buffer

Project opportunity area attributes	Rivers	.shp	Natural Earth	Natural Earth is a public domain map dataset featuring both cultural and physical vector data themes. The rivers datasets are originally from the World Data Bank 2. All rivers received manual smoothing and position adjustments to fit shaded relief generated from SRTM Plus elevation data, which is more recent and (presumably) more accurate. www.naturalearthdata.com/ downloads/	Unknown (version 3.0.0)	
Resource assessment	Population density	raster	LandScan (Oak Ridge National Laboratory)	ORNL's LandScanTM is the community standard for global population distribution. At approximately 1 km resolution (30" X 30"), it is the finest resolution global population distribution data available and represents an ambient population (average over 24 hours).	2012	>100 persons km-2
Resource assessment	Wind	raster	3Tier	Data were created from computer simulations using a meso-scale numerical weather prediction model and validated using publicly available wind speed observations from 194 meteorological stations within Africa from the National Centers for Environmental Prediction (NCEP). Annual wind speed, wind power density, and wind power output were provided at 80 m hub height and 5 km resolution for a typical meteorological year.	10-year model run	<300 W/m2
Resource assessment	Solar DNI	.tiff	3Tier	The dataset is based on actual, half-hourly, high-resolution visible satellite imagery observations via the broadband visible wavelength channel at a 2 arc minute resolution.	15 years	<250 W/m2
Resource assessment	Solar GHI				(1998 – 2013)	<280 W/m2
Resource assessment	Protected Areas	.shp	World Database of Protected Areas (WDPA)	The World Database on Protected Areas (WDPA) is the most comprehensive global spatial dataset on marine and terrestrial protected areas available. The WDPA is a joint project of UNEP and IUCN, produced by UNEP-WCMC and the IUCN World Commission on Protected Areas working with governments and collaborating NGOs.	2014	<500 m buffer
Resource assessment	Protected Areas	.shp	Protected Planet	Open source database that includes most WDPA locations, but also include polygon representations of the WDPA point locations (those with unknown extents/boundaries)	2014	<500 m buffer
Resource assessment	Rail	.shp	Africa Infrastructure Country Diagnostic (AICD) - Africa Development Bank (AfDB) and World Bank (WB)	Primary data collection efforts covering network service infrastructures (ICT, power, water & sanitation, road transport, rail transport, sea transport, and air transport) from 2001 to 2006 in 24 selected African countries.	Variable; compiled 2011	<500 m buffer

Project opportunity area attributes	Roads	.shp	AICD – AfDB and WB	See above rail category	Variable; compiled 2008	
Project opportunity area attributes	Roads	.shp	gROADSv1 -Columbia University	Global Roads Open Access Data Set, Version 1 was developed under the auspices of the CODATA Glo5bal Roads Data Development Task Group at Columbia University. The data set combines the best available roads data by country into a global roads coverage, using the UN Spatial Data Infrastructure Transport (UNSDI-T) version 2 as a common data model.	Variable; compiled 2010 (1980-2010)	
Project opportunity area attributes	Trans-mission	.shp	AICD – AfDB and WB	Transmission lines were only available for a subset of sub-Saharan African countries. In some cases, lines do not represent geographic footprint of transmission lines but are schematics depicting points of interconnection.	Variable - compiled 2010	
Project opportunity area attributes	Renewable energy locations	.shp	AICD – AfDB and WB	Existing and proposed power plants for select sub-Saharan African countries where data were available.	Variable; compiled 2011	
Project opportunity area attributes	Load centers	Lat-long co-ordinates	Geonames	The GeoNames geographical database is available for download free of charge under a creative commons attribution license. It contains over 10 million geographical names and consists of over 9 million unique features including 2.8 million populated places and 5.5 million alternate names (www.geonames.org)	2014	
Project opportunity area attributes	Wind speed time series	.csv	3Tier	Hourly wind speed, wind power density, and wind power output for 10 years (same simulated data that was used to create the typical meteorological year (TMY) average values); approximately 5 km resolution	10-year model run	

Using the default resource assessment thresholds (Table 1), we generated potential areas and approximated potential generation (MWh) using average capacity factors for different thresholds of resource quality, land use factors, and land use discount rates of 25% and 10% for wind and solar technologies, respectively [Black & Veatch Corp. and NREL, 2009]. We chose default criteria thresholds that identify "high" wind and solar resource quality (W/m2) by industry standards [Black & Veatch Corp. and NREL, 2009] [CPUC, 2009], which were meant to identify the highest-potential renewable energy zones across the entire ACEC. However, we separately reduced the resource thresholds and re-estimated resource areas for each country within an economically-viable range if potential generation did not meet the country's 2030 demand projections (Eastern Africa Power Pool (EAPP) et al., 2011; Southern Africa and Nexant, 2007); these are the "lower" values in Table 3. The 2030 demand projections for each country were selected as a common criteria to assess the adequacy of each renewable energy type's resource potential and to maximize the number of options, without suggesting that all demand would be met by renewable energy resources. The year 2030 was selected as a reference year by which significant growth in electricity demand is likely to occur. Thresholds were adjusted to no less than 200, 210, and 230 W/m^2 for wind, solar PV, and solar CSP, respectively (Table 3). In countries where no or little potential was identified, we systematically examined the exclusion criteria and identified the main reasons. For some countries, this step resulted in adjustment of non-resource quality thresholds such as elevation or slope

(Table 3; section 2.9). Additionally, we compared potential areas with mapped locations of existing and potential wind and solar installations and load centers, and adjusted resource quality and elevation thresholds in order to identify potential areas closer to these locations (see section 2.9).

TABLE 2: GlobalMap V2 land use/land cover included (In) and excluded (Ex) categories for all technologies.

Code	Class Name	Solar PV and CSP	Wind	Wind (including agricultural areas)	Criteria score†
1	Broadleaf Evergreen Forest	Ex	Ex	Ex	
2	Broadleaf Deciduous Forest	Ex	Ex	Ex	
3	Needleleaf Evergreen Forest	Ex	Ex	Ex	
4	Needleleaf Deciduous Forest	Ex	Ex	Ex	
5	Mixed Forest	Ex	Ex	Ex	
6	Tree Open	Ex	In	In	4
7	Shrub	In	In	In	3
8	Herbaceous	In	In	In	2
9	Herbaceous with Sparse Tree/Shrub	In	In	In	3
10	Sparse vegetation	In	In	In	1
11	Cropland	Ex	Ex	In	5
12	Paddy field	Ex	Ex	Ex	
13	Cropland / Other Vegetation Mosaic	Ex	Ex	In	5
14	Mangrove	Ex	Ex	Ex	
15	Wetland	Ex	Ex	Ex	
16	Bare area, consolidated (gravel, rock)	In	In	In	1
17	Bare area, unconsolidated (sand)	In	In	In	1
18	Urban	Ex	Ex	Ex	
19	Snow / Ice	Ex	Ex	Ex	
20	Water bodies	Ex	Ex	Ex	

†For project opportunity area and zone scoring purposes, each appropriate LULC category was assigned a value from 1 through 5, with 1 being most suitable and 5 being least suitable.

2.4 CREATION OF PROJECT OPPORTUNITY AREAS (STAGE 2)

Using resource areas generated under modified resource assessment assumptions, we created representative utility-scale "project opportunity areas" (POAs) by dividing contiguous resource areas larger than 25 km^2 using a 5 km square grid for solar and wind technologies, respectively. We merged abutting smaller areas to create larger contiguous areas, and areas less than 2 km^2 were removed from subsequent analysis. After applying land use factors and land use discount factors adopted in this analysis (Table 4), these steps divide large resource areas into POAs that could accommodate power plants between 6 MW and 75 MW of installed capacity for solar and 2.5 MW and 56.25MW for wind.

2.5 ESTIMATION OF PROJECT OPPORTUNITY AREA ATTRIBUTES (STAGE 3)

For each project opportunity area (POA), we estimated several attributes (Table 4) for direct use in multi-criteria scoring of zones or for calculations of capacity factors (section 2.5.7) and costs (section 2.5.8), which are described in greater detail in subsequent sections.

TABLE 3: Adjusted resource assessment thresholds.

Country	Wind W/m2	Solar PV GHI W/m^2	Solar CSP DNI W/m^2	Elevation	Slope	Population	LULC
Angola	200 (lower)	250 (ACEC)	280 (ACEC)				
Botswana	200 (lower)	250 (ACEC)	280 (ACEC)				
Burundi	200 (lower)	230 (lower)	260 (lower)	2500 m	20% (wind and solar)	200 persons per km^2	Include "Tree Open" category
DRC	200 (lower)	210 (ACEC)	260 (lower)	2500 m			
Djibouti	300 (ACEC)	250 (ACEC)	260 (lower)				
Egypt	200 (lower)	230 (lower)	270 (lower)				
Ethiopia	200 (lower)	250 (ACEC)	280 (ACEC)	3000 m			
Kenya	250 (lower)	250 (ACEC)	270 (lower)	2500 m			
Lesotho	200 (lower)	250 (ACEC)	280 (ACEC)	2500 m			
Libya	300 (ACEC)	250 (ACEC)	280 (ACEC)				
Malawi	200 (lower)	240 (ACEC)	260 (lower)	2500 m			
Mozambique	200 (lower)	230 (ACEC)	260 (lower)				
Namibia	200 (lower)	250 (ACEC)	280 (ACEC)				
Rwanda	200 (lower)	230 (lower)	260 (lower)	2500 m	10% (wind)	200 persons per km^2	Include "Tree Open" and "Mixed Cropland" categories
South Africa	300 (ACEC)	250 (ACEC)	280 (ACEC)	2000 m			
Sudan	250 (lower)	250 (ACEC)	280 (ACEC)				
Swaziland	250 (lower)	210 (lower)	260 (lower)				
Tanzania	250 (lower)	250 (ACEC)	280 (ACEC)	2000 m			
Uganda	200 (lower)	250 (ACEC)	260 (lower)	2500 m			
Zambia	200 (lower)	250 (ACEC)	260 (ACEC)	2000 m			
Zimbabwe	200 (lower)	250 (ACEC)	280 (ACEC)				

Highlighted rows in blue indicate no identified potential for the technology.

TABLE 4: Description of estimated project opportunity area (POA) attributes.

Attribute	Description
Area	Total land area of the POA in units of square kilometers
Resource quality	Mean resource quality in terms of wind power density or solar irradiance in units of W/m^2.
Capacity factor(s)	Mean capacity factor of the POA for each sub-technology (e.g., Class II turbine and chosen class turbine for wind, storage or no storage for solar CSP), estimated using average resource quality (section 2.5.7).
Electricity generation	Average annual electricity generation (MWh) estimated using each technology's (and sub-technology's) capacity factor, land use discount factor, and land area.
Road LCOE	Average levelized cost of electricity (in USD/MWh) for the road component, assuming 50 MW of installed capacity per POA (Equation 8 in section 2.5.8).
Interconnection LCOE(s)	Average levelized cost of electricity (in USD/MWh) for the transmission or substation component for each sub-technology (Equation 7 in section 2.5.8).
Generation LCOE(s)	Average levelized cost of electricity (in USD/MWh) for the generation component. Values were estimated using the location and sub-technology's capacity factor and efficiencies specific to the technology (Equation 6 in section 2.5.8).
Total LCOE(s)	Average total levelized cost of electricity estimated by summing the individual component LCOEs for generation, transmission line or substation (values available only if data could be procured), and road.
Distance to nearest location	Straight-line distance from each POA to the nearest transmission line (with 1.3 terrain factor applied); substation (with 1.3 terrain factor applied); road (with 1.3 terrain factor applied); load center; existing or planned wind, solar, or geothermal plant; and surface water body.
Slope	Mean slope of the POA in units of percent rise.
Population density	Mean population density of the POA in units of persons/km^2.
Human footprint score	Mean human influence index metric (0 – least human impact; 100 – most human impact)
Land use / land cover score	Mean score for land use/land cover categories in the zone. Scores range from 1 to 5, with 1 being most compatible for energy development and 5 being least compatible. See Table 2 for the score of each LULC type.
Co-location score(s)	A binary score of 0 or 1, with 1 indicating that a POA is suitable for the development of another renewable energy technology. A score was determined for each of the other renewable energy technologies (e.g., wind and solar PV for a solar CSP POA).
Water access score	A binary score of 0 or 1, with 1 indicating that a POA is within 10 km of surface water.

2.5.1 DISTANCE TO NEAREST ROAD AND TRANSMISSION LINE OR SUBSTATION

In order to estimate transmission and road extension costs, we calculated the Euclidean (straight-line) distance from the nearest edge of each POA to the closest substation and road. We applied a terrain factor of 1.3 to these distances to account for terrain and other development constraints that would dictate the actual path of the extended road or transmission line. We preferred to use distance to substation for estimating interconnection costs if substation data were available for a country. However, separate total LCOEs were estimated for each POA using both transmission and substation data if available. Default transmission line data (AICD or CBI) were only used if country-specific substation or transmission data from the country agency could not be obtained (Table 5). However, AICD or CBI transmission lines may be shown in the interactive maps for reference purposes if transmission data were not provided by country agencies.

TABLE 5: Transmission and substation spatial data availability and sources.

	Default transmission data	Country-specific substations	Country-specific transmission lines
Angola	AICD	N/A	N/A
Botswana	AICD	Botswana Power Corporation	N/A
Burundi	AICD	N/A	N/A
Djibouti	N/A	N/A	N/A
DRC	AICD	N/A	N/A
Egypt	CBI	N/A	N/A
Ethiopia	AICD	N/A	N/A
Kenya	AICD	KETRACO	KETRACO
Lesotho	AICD	N/A	N/A
Libya	N/A	N/A	N/A
Malawi	AICD	ESCOM	ESCOM
Mozambique	AICD	Ministry of Energy	N/A
Namibia	AICD	NamPower	NamPower
Rwanda	AICD	REDC	REDC
South Africa	AICD	Eskom	Eskom
South Sudan	CBI	N/A	N/A
Sudan	CBI	N/A	N/A
Swaziland	AICD	Swaziland Electricity Company (SEC)	Swaziland Electricity Company (SEC)
Tanzania	AICD	N/A	TANESCO (partially complete)
Uganda	AICD	UNEP	UNEP
Zambia	AICD	ZESCO	N/A
Zimbabwe	AICD	ZETDC	N/A

2.5.2 DISTANCE TO MAJOR LOAD CENTRES AND SURFACE WATER SOURCES

We calculated the Euclidean distance to the nearest major load center and surface water source, which may be important considerations in siting a power plant. If countries did not provide load center locations or place names, we selected load centers using the following rules that attempt to accommodate the large population differences between countries: for each country, all cities greater than 100,000 people were identified; if more than 20 cities met this population criteria, the top 20 cities were selected as the major load centers; if less than 20 were identified within the country, the city population threshold was reduced to 50,000 people and the top 20 cities (or fewer) were selected to be the load centers. We used city center geographic coordinates from geonames.org (Table 1). Using the lake, reservoir, and river categories in the Global Lakes and Wetlands Database and all rivers in the Natural Earth rivers dataset (Table 1), we calculated the distance to the nearest surface water source.

2.5.3 DISTANCE TO EXISTING OR PLANNED RENEWABLE POWER PLANTS

Distance to existing or planned renewable power plant for each POA provides an indication of the probability of whether the POA may have already been identified as suitable for renewable energy development by other studies. Locations on existing and proposed power plants locations were requested from all countries in spatial format (polygons, points, or geographic coordinates) and combined with closest location approximation of power plant names found in the academic literature, on government websites, in news articles, and other proprietary information sources such as Cross Border Information (CBI) Africa Energy Atlas [CBI, 2013]. Because we did not model new potential geothermal plants, we did not seek data such as heat flow maps and estimated temperatures at depth below earth's surface. We discovered a paucity of data for existing and planned geothermal projects, despite extensive documentation of geothermal potential in the region (International Renewable Energy Agency [IRENA, 2014]. We collected limited geothermal location data for only seven countries (Ethiopia, Kenya, Malawi, Mozambique, Uganda, Rwanda, Djibouti, and Sudan), but have documented geothermal potential for three additional countries (Burundi, Democratic Republic of Congo, and Tanzania).

2.5.4 LAND USE/LAND COVER

Categorical land use/land cover (LULC) data needed to be converted to scores in order to be averaged over an entire POA land area. A score ranging from 1 (least impactful alteration of LULC) to 5 (most impactful alteration of LULC) was assigned to each LULC category based on social and environmental value (biomass) of particular LULC categories (Table 2). We recognize that these scores are subjective and inadequate proxies for ecosystem services, biodiversity, and other ecological indicators. To address this, we have also provided a human footprint metric that indicates the degree of human disturbance on the landscape, which may be a better proxy for ecological value and intactness given the lack of detailed spatial data on conservation value.

2.5.5 HUMAN FOOTPRINT

The human footprint is a metric for degree of human influence on a unit of land, and it is used in this study as a proxy for degree of human "disturbance" from natural, unaltered states [Sanderson et al., 2002]. We estimated this metric following Sanderson et al.'s (2002) methods, using the following datasets that indicate the degree of human influence and access: population density, land use/land cover, road and railway access, and surface water (rivers and oceans). Datasets were coded into standardized scores ranging from 0 (least influenced) to 10 (most influenced) (Table 6). We did not include the power infrastructure criteria in Sanderson et al. (2002), which relies on nighttime light visibility spatial data. Assumptions about population infrastructure's use as a proxy for population distribution and correlation with human settlements is based on developed countries' widespread electricity availability, which is not the case for many parts of our study region.

TABLE 6: Human Influence Index scoring system for Human Footprint datasets.

Dataset	Scoring system
Population density	Score increased linearly from 0 to 10 persons/km^2; all densities greater than 10 were assigned a score of 10.
Land use land cover	10 – built environments, 9 – cropland and paddy fields, 7 – cropland/mosaic vegetation, 0 – for all other land use land cover categories
Roads and railways	Areas within 1 km of roads and railways were assigned a score of 10, and those areas between 1 and 15 km assigned a score of 4.
Oceans and rivers	Areas within 1 km of rivers or the ocean oceans were assigned a score of 10, and those areas between 1 and 15 km assigned a score of 4.

We summed the scores for each dataset to create a Human Influence Index. Lastly, these scores were normalized within global terrestrial biomes [Olson et al., 2001], since absolute scores in one ecoregion may have a different effect compared to scores in another ecoregion. Within each ecoregion, the lowest Human Influence Index was assigned a human footprint score of 0 and the largest Index value a human footprint score of 100. The resulting human footprint score represents the relative human influence within an ecoregion as a percentage. For example, a score of 1 within the Central Zambezian Miombo woodlands suggests that the area is the top 1% least disturbed or most wild area within the ecoregion. Since we calculated the human footprint score for each 500 m grid cell, we averaged the scores across every grid cell in each POA.

2.5.6 CO-LOCATION AND WATER ACCESS SCORES

For each POA, we used the Euclidean distance to the nearest surface water body (river, freshwater lake, or reservoir) to assign a value of 1 to POAs that were within 10 km of surface water and a value of 0 to those that were not. Previous studies report 10 km as the maximum cost-effective distance to transport water for cooling for solar CSP power plants or washing for solar PV power plants [CPUC, 2009]. To estimate co-location scores for each technology, we overlaid the POAs of the other two renewable energy technologies and assigned scores of 1 if at least 1 km^2 of land overlapped between each set of POAs. For example, when calculating the co-location score of a wind POA, we examined the area overlap between the wind POA and all solar PV POAs to calculate a wind-solar PV co-location score, and separately examined the area overlap between the wind POA and all solar CSP POAs to calculate a wind-solar CSP co-location score.

Remaining criteria—resource quality, population density, and slope—were simply estimated by averaging all grid cell values within a POA.

2.5.7 CAPACITY FACTOR ESTIMATION

SOLAR PV

To estimate solar PV capacity factors (cf_{solar}), we extracted and spatially averaged the resource quality (r) (W/m2) of each project opportunity area for solar PV (Equation 1). Since land use factors that we applied are specified for MW_{ac}, we further applied outage rates (η_o), and inverter and AC wiring efficiencies (η_ι) to estimate the capacity factor for solar PV (Table 7). We assume an incident power density of 1000 W/m^2.

$$cf_{solar} = \frac{(1-\eta_o)\cdot(1-\eta_\iota)\cdot r}{1000} \quad (1)$$

SOLAR CSP

Apart from the type of collector technology (parabolic trough, compact linear Fresnel reflector or heliostat solar tower), the capacity-based land use factor (e.g., MW/km^2) of solar CSP depends on two interdependent variables: the solar multiple and thermal storage. The design capacity of the solar CSP plant is based on the design output of the power turbine block. The solar multiple is the ratio of the actual size of the power plant's solar field to the size of the solar field that would be required to drive the turbine at its nominal design capacity assuming standard solar irradiance of 1 kW/m^2 at standard temperature and pressure.

Thermal storage can significantly improve the capacity factor of the plant and its ability to generate when the value of electricity is greatest, which is the greatest advantage of thermal storage. Thermal storage can enable a CSP plant to store heat during high solar insolation hours and generate electricity during the evening, night or other hours when the sun is not shining. Power plants with thermal storage can have solar multiples of up to 3-5 [IRENA, 2013a]. While such plants have a higher cost per MW due to the additional thermal storage equipment and a larger solar field (i.e., higher solar multiple), they have higher capacity factors compared to plants without thermal storage. CSP plants with no storage are typically designed to have a solar multiple between 1.1 – 1.5 [IRENA, 2013a], which is greater than 1 in order to generate electricity during the morning and evening hours when insolation is lower than threshold requirements, at the expense of losing some excess energy during the peak sun hours.

More thermal storage results in higher capacity factors (CF), but it reduces the land use factor (MW/km^2) due to the increasing solar multiple required. Given the near linear trade-off between thermal storage and land use factor, the generation-based land use factor (MWh/km^2) should be invariant to thermal storage assumptions. Nonetheless, we estimate CFs assuming both storage and no storage. Due to lack of empirical land use factor data for thermal storage systems, we use average empirical land use factors for no-storage CSP plants examined in the USA, which are more robust (as measured by number of data samples), and applied the ratio of storage to no-storage solar multiples to estimate land use factors for CSP plants with thermal storage (Table 7) [Ong et al., 2013].

Models of CSP power plant generation are complex and difficult to approximate using only design calculations and average direct normal insolation (DNI) values. Instead, we used NREL's System Advisor Model [NREL, 2014] to simulate the CF for 45 locations throughout the study region in Africa and five locations in California and Arizona (in order to achieve greater representation of higher DNI regions) for two generic CSP plants with the following assumptions: (1) no storage and a solar multiple of 1.2; (2) 6 hours of storage and a solar multiple of 2.1. Weather data for both U.S. and African locations were available from the U.S. Department of Energy Simulation Software database, a compilation of weather data from multiple sources [U.S. Department of Energy, ud]. We linearly regressed each location's CF against its DNI, wind speed, temperature, and latitude, and determined that DNI was the only statistically significant explanatory variable for trends in CF. We plotted CF against DNI and chose to fit a logarithmic equation to the data because of known increased efficiency losses at the higher end of the DNI range (Figure 5). We used these fitted equations (Figure 5) to estimate the CF for the spatially averaged DNI in each project opportunity area for both no-storage and 6-hr-storage CSP power plant design assumptions.

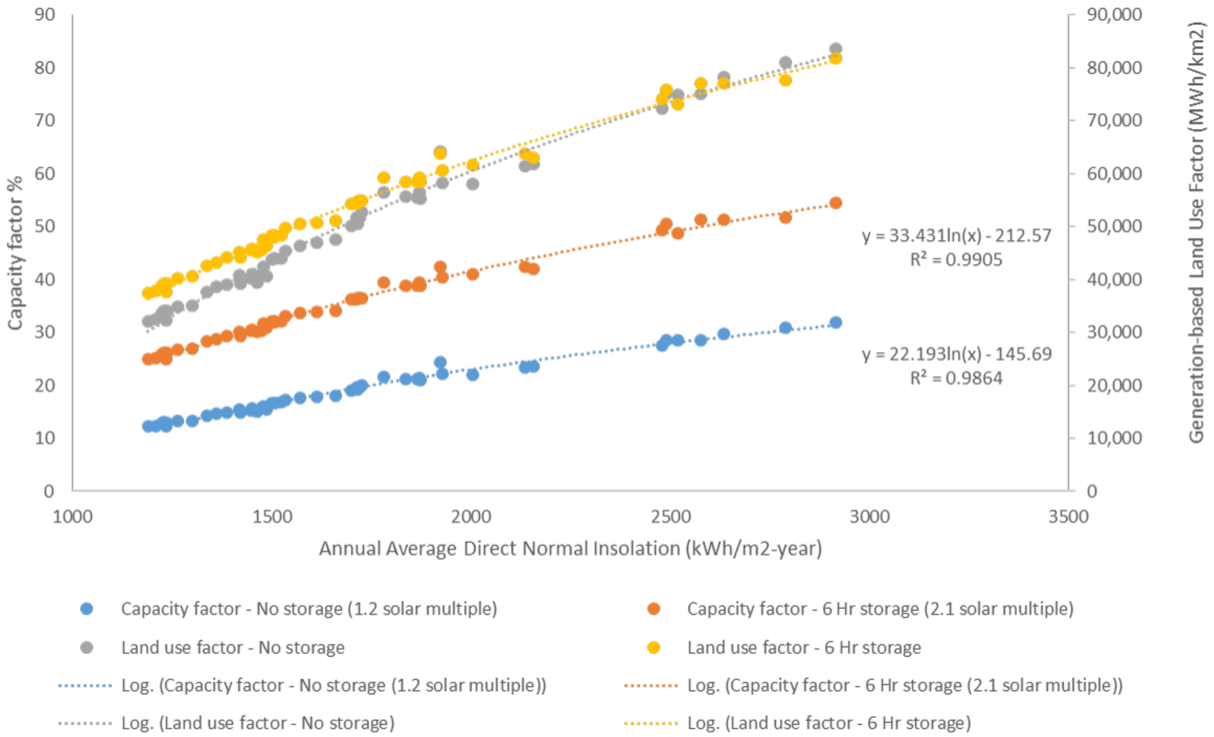


FIGURE 5: Relationship between capacity factor, land use factor, and Direct Normal Insolation (DNI).

Capacity factors were simulated using specifications for a generic CSP plant in the National Renewable Energy Laboratory's System Advisor Model for 45 locations throughout the study region in Africa and five locations in California and Arizona, USA. Logarithmic equations were fit to the simulated capacity factor data to statistically model the relationship between capacity factor and DNI. Land use factors (MW/km^2) on the secondary axis were estimated for each location's capacity factor assuming an installed capacity land use efficiency of 30 MW/km^2 for no storage and 17 MW/ km^2 for 6 hours of storage.

WIND

The capacity factor of a wind turbine installation depends on the wind speed distribution at the wind turbine hub height, the air density at the location, and the power curve of the turbine. We used spatially-averaged shape and scale parameters for the Weibull distribution provided by 3Tier Inc. (now Vaisala Inc.) to generate a wind speed probability distribution per 3.6 km grid cell (the resolution of 3Tier data).

Air density is inversely related to elevation and temperature. It decreases with increasing elevation or temperature, and as a result, can significantly affect the power in the wind for a particular wind speed regime. Wind turbine power curves provided by manufacturers typically assume an air density of 1.225 kg/m^3, which is the air density at sea level and 15 oC. An increase in elevation from sea level to 2500 m can result in 26% decrease in air density. Changes in temperature produce a smaller yet significant effect on air density compared to elevation. A temperature increase from 0° C to 25° C can result in a drop of 8% in air density. To account for the effect of air density on power generation, we first estimated the air density for each grid cell, and then applied power curves modified for different air densities to the wind speed distributions.

For air density, we first estimated the pressure (p) for each grid cell from the elevation and temperature of those grid cells (see Table 2 for sources), the air pressure at sea level (p_o: 101325 Pa), the gravitational acceleration (g: 9.807 kg/m^3), and the gas constant (R: 287.04 J/kg-K) (Equation 2) [Gipe, 2004]. We then estimated the air density (ρ) from the estimated pressure (p), the gas constant and temperature of the grid cell (Equation 3).

$$p = \rho \cdot e^{\frac{-Zg}{RT}} \quad (2)$$

$$\rho = \frac{p}{RT} \quad (3)$$

On-shore wind turbines are generally classified into three International Electrotechnical Commission (IEC) classes depending on the wind speed regimes. We used normalized wind curves for the three IEC classes developed by the National Renewable Energy Laboratory [King et al., 2014] (see Figure 6), and scaled these to a 2000 kW rated wind turbine. Adopting an approach similar to [Wiser et al., 2012], we assumed the IEC Class III and II turbines to be viable in sites up to the reference wind speeds of 7.5 m/s and 8.5 m/s respectively, as defined by the IEC. For sites with average wind speeds above 8.5 m/s, we assumed the IEC Class I turbine to be suitable. In reality, depending on the site-specific gust, turbulence, and air density, IEC Class II and III turbines could be placed at sites with higher average wind speeds than those assumed in our analysis, in order to extract more energy from the wind [Wiser et al., 2012].

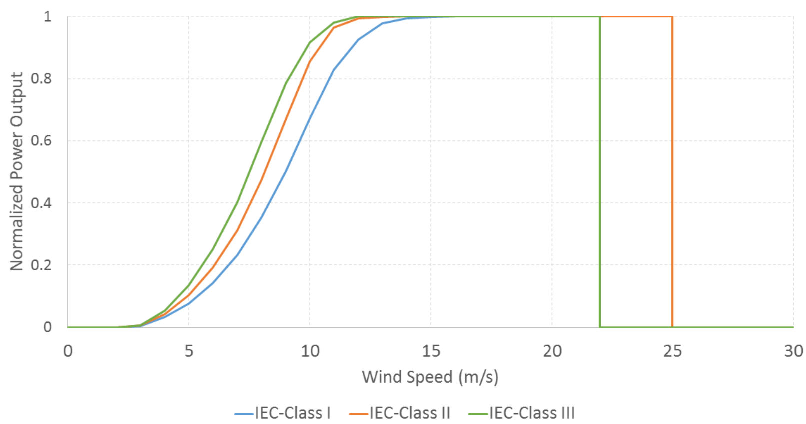


FIGURE 6: Normalized power curves for different IEC class turbines reproduced from [King et al., 2014].

For each of the three turbine classes, we adjusted the power curves for a range of air densities by scaling the wind speeds of the standard curves according to the International Standard IEC 61400-12 [IEC, 1998] [Svenningsen, 2010]. In Equation 4, v_{adj} is the adjusted wind speed, v_{std} is the wind speed from the standard power curve, ρ_{std} is the standard air density of 1.225 kg/m^3, and ρ_{adj} is the estimated air density of the grid cell.

$$v_{adj} = v_{std}\left(\frac{\rho_{std}}{\rho_{adj}}\right)^{1/3} \quad (4)$$

Since the resulting power curve (v_{adj}, P_{std}) is evaluated at the adjusted wind speed values, v_{adj}, we needed to interpolate the P_{adj} at discrete wind speed values (v_{std}) in order to plot the air-density-adjusted power curve (v_{std}, P_{adj}) [Svenningsen, 2010]. The resultant adjusted power curves show that air density can significantly affect the wind turbine power curves, and subsequently, the expected capacity factors at a site (Figure 7).

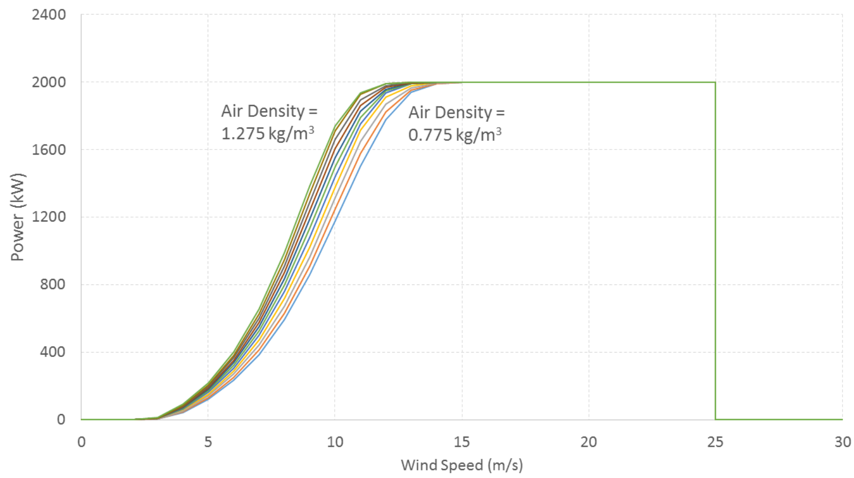


FIGURE 7: Adjusted IEC Class II power curves for air densities ranging from 1.275 kg/m^3 to 0.775 kg/m^3 (from left to right, respectively).

To compute the capacity factor for each 3.6 km grid cell, we selected the appropriate air-density-adjusted power curve given the average wind speed, which determines the IEC class, and the air density, which determines the air-density adjustment within the IEC class. For each grid cell, we then discretely computed the power output at each wind speed given its probability (determined by the Weibull distribution parameters provided by 3Tier) and summed the power output across all wind speeds within the turbine's operational range to calculate the mean wind power output in W ($\overline{P}$). The capacity factor is simply the ratio of the mean wind power output to the rated power output of the turbine (2000 kW), accounting for any collection losses (η_a) and outages (η_o) (Equation 5).

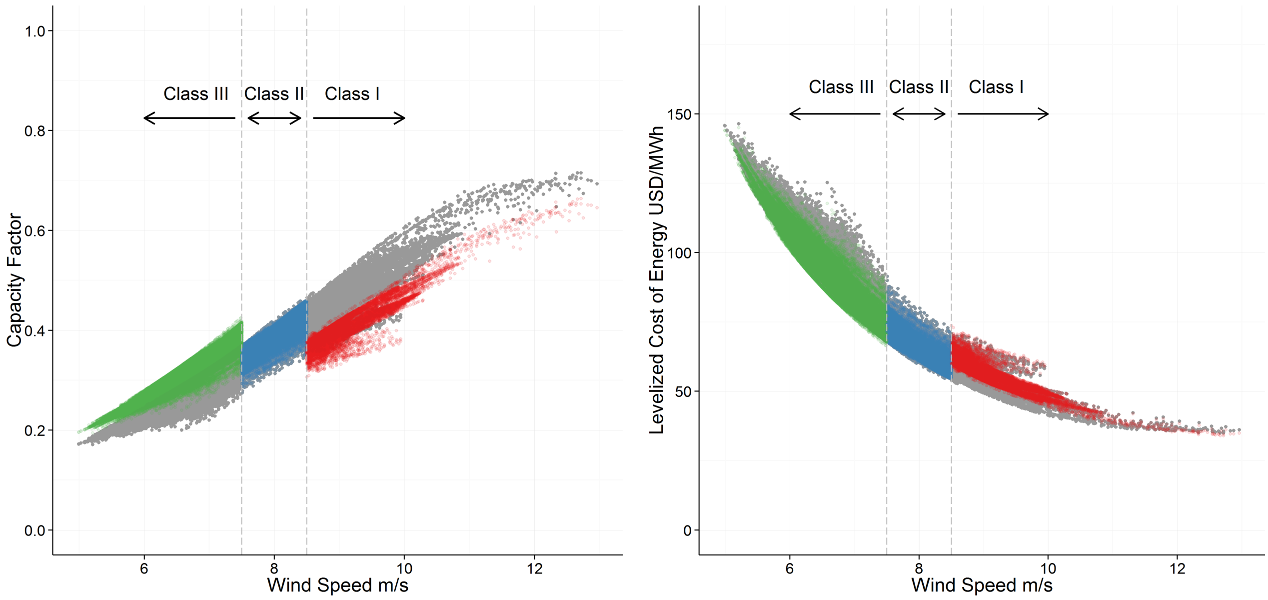
$$cf_{wind} = \frac{(1-\eta_a)\cdot(1-\eta_o)\cdot\overline{P}}{200000W} \quad (5)$$

2.5.8 LEVELIZED COST OF ELECTRICITY (LCOE) ESTIMATES

INPUT COST ASSUMPTIONS

Wind costs - Capital costs for wind can vary significantly across different countries and by IEC turbine class. For Class II turbines, we assumed a cost of $1450 USD per kW (Table 7), which is an approximate capacity-weighted average of the wind projects in South Africa and Namibia, as reported in [IRENA, 2014]. These costs are slightly higher than those observed in China and India, but lower than those reported in the United States and Europe [IRENA, 2013b], which can be explained by the higher labor costs in the U.S. and Europe and the greater maturity of the market in China and India. These values represent project costs that include financing, balance of station costs, in addition to turbine costs. Using literature values, we adjusted the standard IEC Class II turbine cost to estimate project costs for IEC Class I [Vaasa Energy Institute, 2011] and IEC Class III turbines [Lantz et al., 2012] [Wiser et al., 2012]. We assumed fixed O&M costs of $60 USD per kW per year for wind turbines [Black & Veatch Corp. and NREL, 2012].

The lower wind speed Class III turbines typically have higher hub heights and larger rotors compared to Class II turbines, resulting in higher capacity factors but also higher capital costs [Wiser et al., 2012]. In our analysis, we have assumed a larger rotor diameter for the lower wind speed Class III turbines. However, we assumed the same hub height of 80m for all three classes, since our wind resource data is modelled at 80m, and it enables a fair comparison between two sites that may be suitable for two different IEC class turbines. Further, a Class I turbine has a similar rotor diameter compared to a Class II turbine, but it has a larger generator rating resulting in lower per megawatt capital cost. In the lower wind speed regime, Class III turbines have higher average CFs compared to Class II turbines, but the decrease in LCOE for Class III turbines is less dramatic due to a corresponding increase in capital costs for a turbine with a larger rotor diameter. In the higher wind speed regime, Class I turbines that are designed to withstand high speeds may have lower average capacity factors compared to Class II turbines, especially at wind speeds between 8.5 and 10 m/s, but their LCOE may not be much higher due to lower capital costs per installed capacity for Class I turbines (Figure 8). In reality, depending on the site-specific gust, turbulence and air density, IEC Class II and III turbines could be placed at sites with higher average wind speeds than those assumed in our analysis, resulting in higher capacity factors [Wiser et al., 2012].



(a) (b)

FIGURE 8: Relationship between average wind speed and estimated capacity factor (A) and levelized cost of energy (B) across the Africa Clean Energy Corridor.

Capacity factors and LCOEs estimated using the wind-speed-appropriate Class I, II and III turbines power curves are represented by red, blue and green points respectively. Capacity factors and LCOEs estimated using just the Class II turbine power curve is also represented by grey points across the wind speed regimes.

Solar PV costs - Capital costs for solar PV have rapidly reduced recently, due to both technology advances and overcapacity. Although projects in SAPP have reported a relatively high capital cost of $4000 USD per kW [IRENA, 2014], we assumed a much lower capital cost of $2000 USD per kW, which is comparable to costs reported in India, China and Germany [IRENA, 2013b]. Further, we assumed $50 USD per kW per year as fixed O&M cost for solar PV plants [Black & Veatch Corp. and NREL, 2012].

Solar CSP costs - Solar CSP capital costs vary significantly depending on the type of technology, thermal storage, and region-specific factors. Because parabolic trough is the most widely used solar CSP technology, we assumed capital costs of $3400 and $7400 USD per kW, as reported for parabolic trough projects without storage and with 6 hours of storage, respectively, in developing countries [IRENA, 2013b]. We also assumed $50 USD per kW per year and $4 USD per MWh as fixed and variable O&M costs respectively for solar CSP plants [Black & Veatch Corp. and NREL, 2012] [NREL, 2014].

Transmission costs - The cost of a transmission line depends on the voltage, capacity and length of the line, the type of conductor, the structure of the poles, the terrain, and the cost of right-of-way, amongst other factors that are location or region specific, such as financing and material costs. For our analysis, we simplified these inputs to calculate the cost of transmission as a function of its length alone, holding all other cost parameters constant. Further, we added the cost of the substations, which does not vary by distance, to the transmission line costs. While including the transmission cost in the LCOE for each project opportunity area enabled us to consider the distance of these areas from existing and proposed transmission infrastructure, the actual transmission costs for an area will need to be computed by giving due consideration to all the factors mentioned above. In selecting a transmission cost value, we considered costs from the U.S. [Black & Veatch Corp. and NREL, 2012], Zimbabwe [ZETDC, 2014], and SAPP [IRENA, 2013c]. Due to their negligible contribution to total LCOE, we omitted the O&M costs for transmission and roads in estimating the LCOEs.

Road costs - The cost of roads can vary widely depending on the type of road, terrain, and region-specific factors such as labor costs and financing. We assumed the median of paved road construction costs for sub-Saharan Africa reported by the Africa Infrastructure Country Diagnostic (AICD) [Africon, 2008]. These costs are similar to those reported by [Alexeeva et al., 2008].

TABLE 7: Parameters in levelized cost of electricity estimates

	Wind			Solar PV	Solar CSP	
Land use factor [MW/km²] (LF)	9[1]			30[2]	No-storage	6-hr-storage
					30[2]	17[3]
Land use discount factor (LDF)	75%			90%	90%	
Costs						
Generation – capital [USD/kW] (C_g)	Class I	Class II	Class III	2000[4]	No-storage	6-hr-storage
	1250[4]	1450[4]	1700[4]		3700[5]	7400[5]
Generation – fixed O&M [USD/MW/y] ($OM_{f,g}$)	60000[4]			50000[4]	50000[4]	
Generation – variable O&M [USD/MWh] ($OM_{v,g}$)	-			4[9]	-	
Transmission – capital [USD/MW/km] (C_t)	990[6]			990[6]	990[6]	
Transmission – fixed O&M [USD/km] ($OM_{f,t}$)	-			-	-	
Substation – capital [USD / two substations (per new transmission connection)] (C_s)	71000[6]			71000[6]	71000[6]	
Road – capital [USD/km] (C_r)	407000[7]			407000[7]	407000[7]	
Road – fixed O&M [USD/km] ($OM_{f,r}$)	-			-	-	
Economic discount rate (i)	10%[8]			10%[8]	10%[8]	
Outage rate (η_o)	2%[9]			4%[9]	4%[9]	
Inverter efficiency and AC wiring loss (η_ι)	-			4%[8]	-	
Array and collection loss (η_a)	15%[10]			-	-	
Lifetime [years] (N)	25[8]			25[8]	25[8]	

[1] Mean of U.S. empirical values (3 MW/km²) [Ong et al., 2012] and theoretical land use factors [Black & Veatch Corp. and NREL, 2009]
[2] [Ong et al., 2012]
[3] Estimated from no-storage land use factor by multiplying by the ratio of no-storage to 6-hr-storage solar multiples (2.1/1.2)
[4] For Class II turbine: [Black & Veatch Corp. and NREL, 2009] . See [Vaasa Energy Institute, 2011] for decrease in Class I turbine cost, and [Lantz et al., 2012], [Wiser et al., 2012] for increase in Class III turbine costs, relative to Class I turbine costs.
[5] [IRENA, 2013b]
[6] [Black & Veatch Corp., 2012]
[7] [Africon, 2008]
[8] [IRENA, 2013c]
[9] Default value in the System Advisor Model (SAM) by NREL [NREL, 2014]
[10] [Tegen et al., 2013]

COST CALCULATIONS

Using the size (km²) of the project opportunity area (a) and its associated land use factor (LF) and land use discount factor (LDF), distance to nearest substation (or transmission line; d_s) and road (d_r), and economic parameters listed in Table 7, we calculated the generation, interconnection and road components of the levelized cost of electricity (LCOE in USD/MWh). The LCOE is a metric that describes the average cost of electricity for every unit of electricity generated over the lifetime of a project at the point of interconnection. Note that the size (km^2) of a project opportunity area (a) and its associated land use factor (LF) and land use discount factor (LDF) cancel out in the LCOE equations, but are included for completeness to show the ratio of cost to electricity generation (Equations 6, 7, 8).

Road LCOE was estimated using a fixed capital cost per km of additional road needed to service the project, and are expressed per unit of electricity output from the project. Since road capital costs do not scale according to installed capacity of a project, unlike generation and interconnection costs which increase with each additional MW of capacity, the size of a project opportunity area affects the road cost. That is, a POA within 10 km of existing road infrastructure will have a higher road cost than another POA within the same distance of the nearest road if it is comparatively smaller in land area. In order to allow road LCOEs to vary only by each POA's road connection distance and resource quality, we assumed 50 MW of capacity per POA regardless of size (Equation 8). We assumed that one road will be built for every 50 MW capacity project, which is a reasonable size for a utility-scale project, and roughly equal to the potential capacity of a project opportunity area. Total LCOE is simply the sum of the generation, interconnection, and road cost components. Equations 6, 7 and8 show LCOE calculations. We prioritize distance to nearest substation in estimating transmission LCOE when high-quality spatial data for substations were available, but we also estimate transmission LCOE costs based on distance to the nearest transmission line. Refer to Table 7 for definitions of cost notation.

$$LCOE_{generation} = \frac{a \cdot LF \cdot (1 - LDF) \cdot (C_g \cdot CRF + OM_{f,g})}{a \cdot LF \cdot (1 - LDF) \cdot cf \cdot 8760} + OM_{v,g} \tag{6}$$

$$LCOE_{interconnection} = \frac{a \cdot LF \cdot (1 - LDF) \cdot (d_s \cdot (C_t \cdot CRF + OM_{f,t}) + C_s \cdot CRF)}{a \cdot LF \cdot (1 - LDF) \cdot cf \cdot 8760} \tag{7}$$

$$LCOE_{road} = \frac{d_r \cdot (C_r \cdot CRF + OM_{f,r})}{cf \cdot 50MW \cdot 8760} \tag{8}$$

The capital recovery factor (CRF) converts a present value to a uniform stream of annualized values given a discount rate and the number of interest periods. We have assumed a real discount rate of 10% that reflects the high cost of capital in Africa.

$$CRF = \frac{i\,(1+i)^N}{(1+i)^N - 1} \tag{9}$$

LIMITATIONS

Although LCOE assumptions were selected to be as representative of current conditions and costs, we intended for these LCOE estimates to be used to compare costs within a single technology since LCOE values may be higher or lower than others reported in the literature given the dynamic nature of the industry. Further, the discount rate can significantly affect the LCOE, and can vary across countries. In the results section, we estimate the sensitivity of the LCOE to the discount rate in addition to other input assumptions (section 3.4).

System integration costs or balancing costs are not included in the analysis. These can vary across countries based on their electricity generation mix. For example, hydro capacity with storage is considered more flexible than coal power plants that typically incur a higher penalty for cycling in order to balance both variable renewable energy and load (net load).

LCOE does not account for differences in the value of electricity generated by different technologies in a particular location. Generation at different times of the day or year have different economic value depending on the demand and the available generation at that time. However, we addressed this separately using capacity value estimates (section 2.5.7).

LCOE estimates are based on present existing and planned transmission and road infrastructure. In this study, we did not value a project opportunity area sequentially based on the utilization of infrastructure that may be built earlier for another nearby planned project.

2.6 CREATION OF ZONES (STAGE 4A)

We used three criteria to create zones from project opportunity areas: size, spatial proximity, and resource quality. The outcome of this process was zones created on the basis of spatial proximity as well as similarity in resource quality. This criteria-based spatial clustering of project opportunity areas increases the representativeness of the average zone resource quality, and thus its average capacity factor and generation LCOE, by reducing the intra-zone variability of these criteria. Defining zones along these meaningful criteria allows the subsequent ranking analysis to distinguish the high potential zones from the low potential zones.

2.6.1 CREATION OF PRELIMINARY ZONES BASED ON SIZE AND PROXIMITY

We first grouped project opportunity areas by spatial proximity such that all projects within 5 km were grouped into preliminary zones (Figure 9). Project opportunity areas (POAs) that comprised preliminary zones with area less than 30 km^2 (70 – 90 MW) were deemed too small for zoning and excluded from the remainder of the analysis. POAs in preliminary zones with areas between 30 km2 (approx. 70 – 90 MW of discounted wind or solar installed capacity) and 350 km^2 (approx. 790 – 1050 MW of discounted wind or solar installed capacity) were set aside and treated as "small" zones. We selected the minimum value based on the capacity available on a 132 kV single circuit transmission line (100 MW) and the maximum value based on the capacity available on a 500 kV single circuit line (900 MW).

2.6.2 CREATION OF ZONES BASED ON SIZE, PROXIMITY, AND RESOURCE QUALITY

POAs in preliminary zones greater than 350 km^2 were re-aggregated into final zones using a regionalization algorithm that creates clusters based on selected POA attributes—resource quality and spatial proximity. We clustered POAs using the "Spatial 'K'luster Analysis by Tree Edge Removal" (SKATER) function in the R programming package 'spdep' [Assuncao et al., 2007]. The regionalization algorithm requires three parameters: the number of nearest neighbors, minimum zone size, and the number of zones to create. We selected the minimum number of nearest neighbors to maintain spatial contiguity, and set a zone minimum area requirement of 160 km^2 (half of the threshold zone size for clustering). The number of zones to create was determined using the total area of the preliminary zone for clustering. Two zones were created if the total area ranged from 350 to 1000 km^2, three zones were created if total area ranged from 1000 to 2000 km^2, and areas greater than 2000 km^2 used the following calculation: $n = roundup\left(\frac{area}{1000}\right)$. POAs within clustered zones greater than 700 km^2 were then re-clustered in a second iteration of the regionalization algorithm, but using 700 km^2 as the minimum area for total areas greater than 1500 km^2 and 350 km^2 as the minimum area for total areas less than 1500 km^2. We chose to perform the clustering twice to allow smaller areas that are homogenous in resource quality to be clustered in the first iteration under a lower minimum size threshold, then allow the higher minimum threshold size in the second iteration to generate larger areas homogenous in resource quality. Final zones created through the clustering process and "small" zones identified using only size (section 2.6.1) were merged for each technology within a country. See Figure 9 for the zone creation process flow diagram. SKATER-clustered zones were manually post-processed to ensure that they did not exceed 100 km in diameter and maintained a high degree of spatial contiguity and resource quality homogeneity.

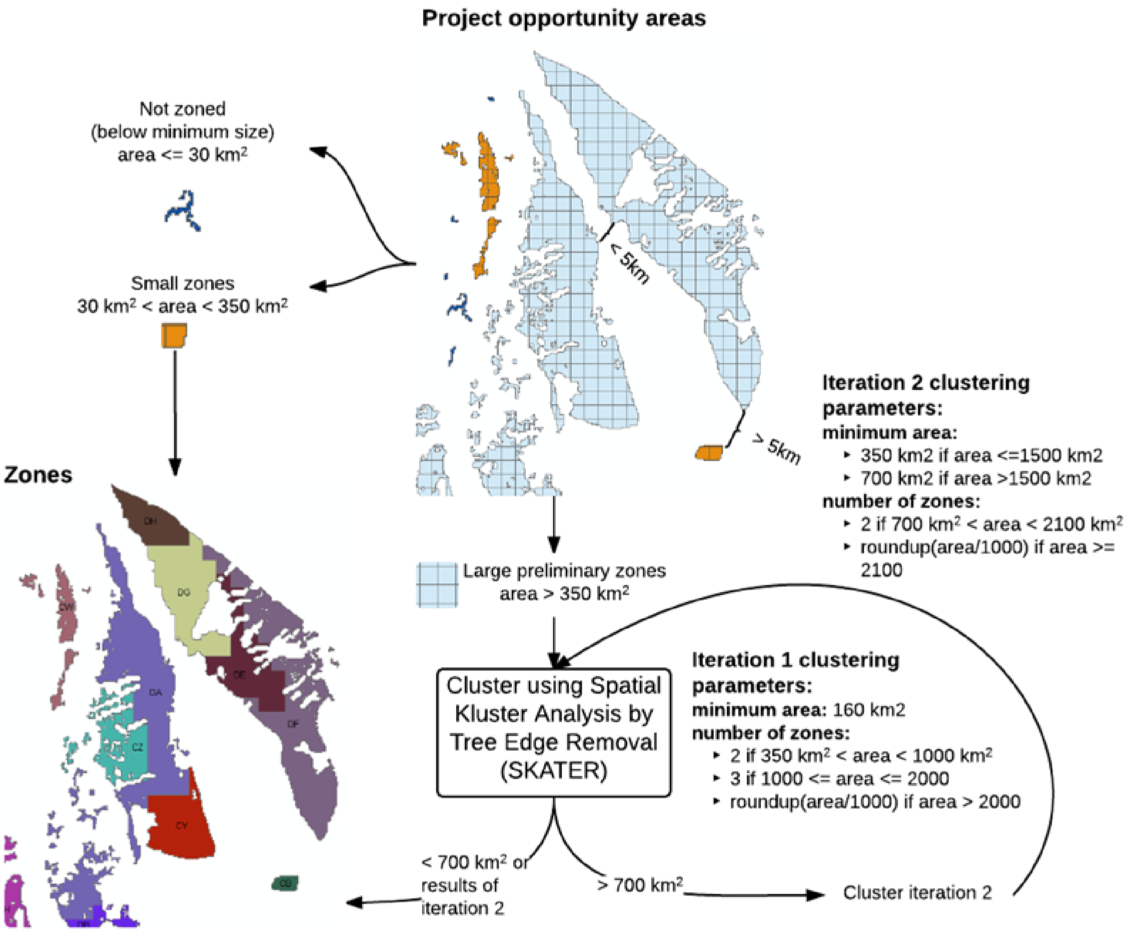


FIGURE 9: The zone creation process using size, spatial proximity, and resource quality of project opportunity areas.

Final zones are labeled using unique zone identification letters that correspond to zones in the multi-criteria scoring zone-ranking tool. Colors of project opportunity areas indicate area of clustered project opportunity area and whether the clusters will be excluded (not zoned), aggregated into small zones, or re-aggregated using the SKATER clustering algorithm based on size.

We made modifications to this zoning creation process for two cases: technologies in countries with large areas of resource potential (e.g., solar PV in Egypt, Namibia, South Africa, Botswana, Ethiopia), and technologies in countries with small areas of resource potential (e.g., wind in Swaziland, Tanzania, Uganda). For the former, we buffered 50 or 100 km around the transmission network (or substation, when transmission data were unavailable) and only zoned project opportunity areas within this buffer. We only did this for countries and technologies that had large areas of high-quality potential and where it makes economic sense to pursue the abundance of those resources close to existing infrastructure. For the latter, we changed the size criteria for the zone creation process to the following: project opportunity areas within preliminary zones less than 10 km^2 (22.5 – 30 MW) were deemed too small for zoning and excluded from the remainder of the analysis; POAs in preliminary zones between 10 km^2 and 100 km^2 were set aside and treated as "small" zones; preliminary zones above 100 km^2 were clustered using the SKATER algorithm using a minimum zone size of 40 km^2 and a maximum zone size to cluster in iteration 2 of 200 km^2; and the number of zones to create followed a modified equation ($n = roundup\left(\frac{area}{200}\right)$).

Zone sizes are not meant to imply that the entire potential capacity of zones must be developed, but instead provide an estimate of the maximum installable capacity in a broad, contiguous suitable area similar in resource quality. After the highest scoring zones have been identified, zones can be further refined to identify candidate sites for on-the-ground surveys by examining POA-level criteria values.

2.6.3 CALCULATION OF ZONE ATTRIBUTES (STAGE 4B)

In order to generate area-weighted zone average attribute values, we area-weighted each of the attributes listed in Table 4 for each project opportunity area within a zone and summed them for each zone. Attributes that were summed across POAs within a zone, rather than averaged, included land area, electricity generation, installed capacity, and water score. The zone water score represents the number of POAs within 10 km of surface water.

2.7 CAPACITY VALUE ESTIMATION (STAGE 5)

The concept of capacity value was developed to quantify the contribution of different generation technologies towards supporting the demand of the utility or balancing area. It was initially used for conventional generation technologies, where the capacity value depended mainly on the forced and maintenance outage rates of the conventional generators. Capacity value is now increasingly used to value variable renewable energy sources, to reward or favor those resources that contribute more towards system reliability due to their higher correlation with system demand. Due to the variability of wind and solar resources, the capacity value of renewable energy generators is less than conventional generators such as coal and natural gas. At the same time, if the capacity value of these renewable energy generators is assumed to be zero for planning purposes, it might lead to overcapacity of generation.

Effective load carrying capability (ELCC) is a metric that is often used to determine capacity value [Keane et al., 2011] [Milligan and Porter, 2008]. ELCC of the renewable energy generator can be defined as the additional load that a megawatt of that generator at a particular site can support to maintain the same level of system reliability. For appropriately assessing the capacity value of renewable energy generation using ELCC, probabilistic methods using power system stochastic simulation for analyzing generation adequacy need to be employed. However, these methods are data and computationally intensive. Simplified methods can provide useful, approximate results without the computational demand and detailed power systems data. They can also be more transparent and provide direct insights into what is driving the results [Dent et al., 2010]. Since one of the main purposes of this study is to robustly compare zones within a country and across the ACEC, relative capacity values of zones is more useful than the absolute values. Because these simplified methods lack a power systems model of the national grid, they more reliably discern differences between zones' generation profiles rather than absolute contribution to system reliability. We restrict the capacity value analysis to wind energy, given the limitations in the scope of this study. The choice of wind technology is justifiable due to the higher predictability and correlation of generation profiles across the region for solar PV, and significantly lower variability for solar CSP with 6 hour storage.

2.7.1 SELECTION OF SITES WITH HOURLY WIND PROFILES

Estimation of capacity value required both time series data for demand and wind generation. We used simulated hourly wind speed data for 400 sites across the ACEC provided by 3Tier. The number of sites was limited due to the scope of the study. After identifying zones for each country, we selected these 400 sites by considering the highest quality project opportunity area within each zone, spatial representation across a country, amount of resource within a country, and locations of existing and planned project sites.

2.7.2 CAPACITY VALUE RATIO

In our simplified approach, we defined the capacity value of the renewable energy generator as a ratio of the average generation during the defined peak demand hours to the nameplate capacity of the generator. The units of capacity value are the same as that of capacity factor, usually expressed as a percentage.

Further, we define the capacity value ratio as the ratio of the capacity value to the average annual capacity factor at the site. The capacity value ratio is used in conjunction with the capacity factor of a zone to determine the contribution of the generation profile to meeting demand during peak hours. By estimating the capacity value ratio for a wind zone by extrapolating it from the nearest of the 400 3Tier wind sites, we assume that the wind zone has a similar hourly generation profile as that site, but it may have a different capacity factor depending on its average wind speed, air density and other factors.

We define three metrics for the capacity value and capacity value ratio. For the first metric, we define capacity value as the average capacity factor of a renewable energy generator during the top 10% of peak demand hours in a year [Mills et al., 2010]. For the second metric, we estimate the capacity value as the average capacity factor during three specific peak demand hours in a day over the course of a year. For those countries that provided hourly demand data, we chose the top three peak demand hours in a day based on their annual demand profile. For those countries that did not provide hourly demand data, we used the top three peak demand hours observed in the majority of the countries within their respective power pools. We repeated the estimation procedure of the second metric for the third metric, but using 3Tier hourly wind data over ten years, as opposed to one year. We computed the capacity value ratios as the ratio of the capacity value to the capacity factor at the site for all three metrics. Finally, we extrapolate the capacity value ratios of the 400 wind sites to all the wind zones based on proximity.

The wind generation profile of a site can significantly affect the degree of its contribution to meeting demand. Figure 10 shows the capacity value and capacity value ratios for three different sites in Kenya, and the extent of their contribution during the top 10% peak demand hours. On one hand, site 1 has the lowest average capacity factor amongst the three sites, but it has the highest capacity value ratio. On the other hand, although average capacity factor for site 3 is the highest, its capacity value ratio is the lowest. Site 2 has the highest capacity value amongst the three sites during the top 10% peak demand hours.

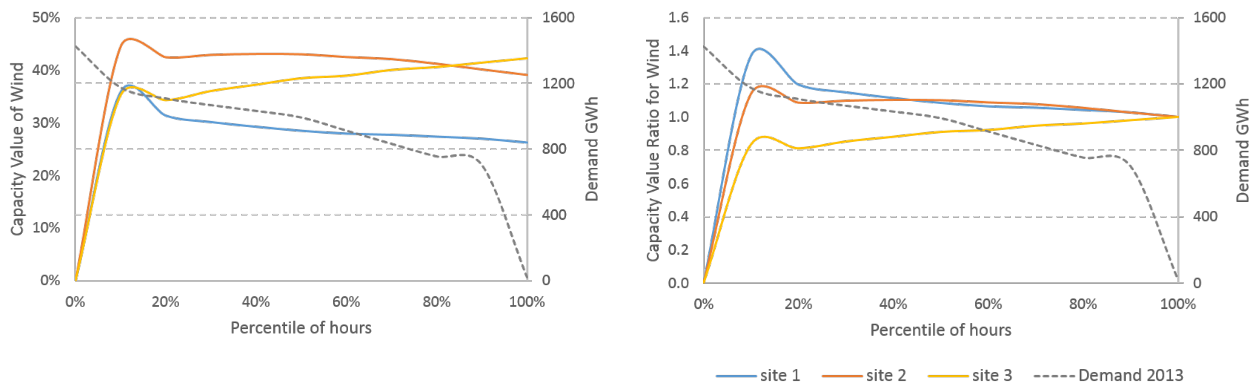


FIGURE 10: Capacity value (left) and capacity value ratios (right) for three different wind sites in Kenya

These capacity value metrics do not capture the seasonal contribution of wind towards meeting demand. While these metrics provide an indication of the potential annual contribution of the wind zone towards meeting peak demand, we advise conducting a more detailed analysis on the variability of wind with detailed datasets.

2.8 MULTI-CRITERIA SCORING

In order to examine how the weighting of different criteria alters the overall suitability of zones, we created a scoring system to evaluate zones within and across the ACEC. Scoring enables the combination of the component and total LCOEs with other criteria that improve site suitability, but cannot be directly monetized. Such attributes include slope; population density; land use/land cover; human footprint score, proximity to existing and proposed solar, wind and geothermal sites;

overlap with other technologies' resource potential; and capacity value (Table 4).

We assigned criteria scores between 0 and 1 to each attribute value, with 0 being least suitable and 1 being most suitable, assuming criteria scores vary linearly within the criteria value range (Table 8). For component and total LCOE and capacity value, the criteria value ranges are based on minimum and maximum values within each technology for each country or across the ACEC. Co-location scores range from 0 to 1 such that no overlap generates a score of 0, complete overlap with one technology generates a score of 0.5, and complete overlap with two technologies generates a score of 1. Other criteria ranges use minimum and maximum values based on exclusion thresholds used in the resource assessment stage (Table 8).

TABLE 8: Criteria value ranges and scores

Criteria	Criteria value range (score)
Slope	0% (1) – 5% (0) for solar; 0% (1) – 20% (0) for wind
Population density	0 (1) - 100 (0) persons/km^2
Land use / land cover	See corresponding LULC categories in Table 2: 1 (1) – 5 (0)
Human footprint	0 (0) to 100 (1)
Overlapping potential with other renewable energy technologies	No overlap (0), overlap with one technology (0.5), or overlap with two technologies (1).
Distance to proposed or existing solar, wind, or geothermal plant	0 km (1) - 25 km (0)
Distance to nearest load center	0 km (1) - 100 km (0)
Distance to transmission or road infrastructure	0 km (1) - 100 km (0)
Number of project opportunity areas within 10 km of water	0 (0) – 10 (1) project opportunity areas
Capacity value ratio	Minimum (0) and maximum (1) value of the ratio of capacity value to capacity factor of each technology by country or across the ACEC
Generation LCOE	The minimum (1) and maximum LCOE (0) of each technology by country or across the ACEC
Transmission/substation LCOE	The minimum (1) and maximum LCOE (0) of each technology by country or across the ACEC
Road LCOE	The minimum (1) and maximum LCOE (0) of each technology by country or across the ACEC
Total LCOE	The minimum (1) and maximum LCOE (0) of each technology by country or across the ACEC

2.8.1 INTERACTIVE PDF MAPS AND ZONE RANKING TOOLS

To allow users to set weights that reflect the relative importance of each criteria in Table 8 and generate a cumulative suitability score, we created a multi-criteria zone ranking tool for each country. Figure 11 offers an example of possible criteria weights. These weights are multiplied by the criteria scores to generate a resultant cumulative suitability score for each zone that is any real value between 0 and 1. Users may then identify the location of the highest ranking zones using the unique zone identification letters and the interactive PDF map's analysis tools.

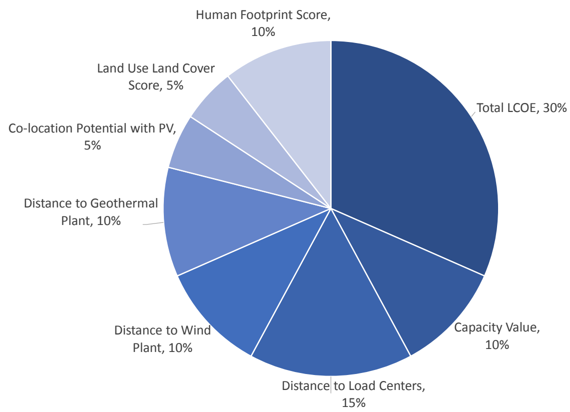


FIGURE 11: Example of zoning criteria weights used to calculate cumulative suitability score.

2.9 COUNTRY-SPECIFIC ANALYSIS ADJUSTMENTS

We adjusted the assumptions in the methodology for several countries based on the feedback from the stakeholder process, as well as considerations from previous studies.

Angola Wind potential is constrained by the resource quality. No adjustments were made to the exclusion criteria.

Botswana Because Botswana has significant PV and CSP potential, we created zones for project opportunity areas within 100 km of substations.

Burundi Using default assumptions for resource assessment yielded no utility-scale wind or solar potential in Burundi, despite its high solar irradiance. Relaxing elevation and slope to 2500 m and 10%, respectively, did not identify potential areas. Additionally relaxing the LULC constraint to include "Tree Open" areas and the population threshold to 200 persons/km2 did allow for utility-scale solar PV development. DNI values greater or equal to 260 W/m^2 does not exist within the country.

Democratic Republic of Congo Because wind resource in DRC is poorer than average, we relaxed the elevation constraint to 2500 m to identify potential in more mountainous areas. However, slope above 20% remained a constraint. We relaxed GHI resource threshold to 230 W/m^2 to identify potential solar PV areas near the capital city of Kinshasa.

Djibouti We identified no CSP potential due to low DNI within the country (<260 W/m^2). Because no country-provided or default transmission or substation data were available, total LCOE could not be estimated for Djibouti.

Egypt Although Egypt has significant wind, solar PV, and CSP potential, we relaxed the wind power density threshold to 200 W/m^2 and the PV threshold to 230 W/m^2 in order to identify wind potential in areas overlapping with and closer to planned and operational wind farms and solar PV areas closer to load centers and transmission lines.

Ethiopia Elevation was relaxed to 3000m due to the high elevation of many sites (>2800 m) selected for reconnaissance in the Hydrochina wind and solar assessment report (2012). Though significant wind potential exists within Ethiopia at 300 W/m^2, those areas are found in eastern Ethiopia, far from major load centers and in an area of current civil unrest. As such, we reduced the wind power density threshold to 200 W/m^2.

Kenya Although the country has adequate wind potential, we relaxed the wind power density threshold to 250 W/m^2 and the elevation threshold to 2500 m to ensure that areas near major load centers and existing and planned wind farms were identified in our analysis (e.g. Ngong Hills near Nairobi).

Rwanda We relaxed elevation to 2500 m, but LULC, slope, and population density remained significant constraints to utility scale PV potential within Rwanda. We relaxed these three constraints in order to identify areas that overlapped with planned and existing small scale solar PV plants (Table 3). Both DNI and wind power density values within the country are below the minimum threshold levels.

Lesotho Because Lesotho is a high elevation country, we relaxed the elevation threshold to 2500 m. Though DNI and GHI levels are high, slope is a constraint for solar development.

Libya Because no country-provided or default transmission or substation data were available, total LCOE could not be estimated for Libya.

Malawi We relaxed elevation constraint to 2500 m in order to capture wind areas in the northern mountains. Solar CSP and wind resource quality are low according to 3Tier resource data, hence fewer areas were identified for these technologies.

Mozambique Inclusion of agricultural land increases the wind potential significantly. LULC exclusions limit the land availability for Solar CSP development. GHI was relaxed to 230 W/m2 in order to capture some resource areas close to the southern load centers.

Namibia Because Namibia has tremendous solar PV and CSP resources, we restricted zone creation to project opportunity areas within 50 km of existing transmission lines. Transmission lines greater than or equal to 66 kV were included. Substations connected to these transmission lines were included (those not-connected to a transmission line greater than or equal to 66 kV were removed).

South Africa Because of the large potential of solar CSP and PV, areas which encompass most of northwestern South Africa, we restricted zoning analysis to CSIR's identified renewable energy focus areas. Elevation threshold was relaxed to 2000m for all technologies to capture wind resource areas in central South Africa and areas close to Lesotho.

Sudan Although the country has adequate wind potential over the threshold of 300 W/m^2, we relaxed the threshold to 250 W/m^2 to ensure that areas such as Jebel Marra Mountains were captured in our analysis. For wind, areas close to some existing and planned wind farms (e.g., Dongola) were not identified due to lower quality resources not captured by3Tier's mesoscale dataset. Sudan's wind atlas does not share significant overlap with 3Tier's mesoscale dataset. Because Sudan has significant PV and CSP potential, we restricted zoning to areas within 50 km of transmission.

Swaziland GHI was relaxed to 210 W/m^2 (equivalent to 5 kWh/m^2/day) since solar insolation was the constraining factor for PV potential in Swaziland. Potential equal to or greater than 210 W/m^2 is considered an economically viable level of source resource. No areas with DNI above 260 W/m^2 exist within the country. The low resource parameter exceptions were applied to both solar PV and wind POAs in the zone creation process.

Tanzania We relaxed the elevation threshold to 2000 m as some high-quality wind sites close to transmission and load centers were excluded due to elevation in the 1500 – 2000 m range.

Uganda The elevation constraint was relaxed to 2500m in order to identify wind potential in the northern and eastern Uganda. For solar CSP and wind, resource quality (DNI and wind power density) is the limiting factor. The low resource parameter exceptions were applied to all technologies' POAs in the zone creation process.

Zambia We relaxed elevation to 2000 m to identify high-quality wind in high elevation regions. Forest and cropland also cover significant areas of Zambia and are the main constraints for solar CSP potential.

Zimbabwe Wind does not face major exclusion constraints, but including agricultural land does significantly increase resource areas in the north. However, we reduced the wind threshold to 200 W/m^2 to identify more wind resource options in central Zimbabwe closer to load centers and transmission lines.

3 RESULTS

3.1 RESOURCE ASSESSMENT

From the resource assessment analysis wherein renewable energy resource areas (areas suitable for renewable energy development) were identified using various criteria described in section 2.3, we determined that abundant wind, solar PV, and solar CSP potential exists within the Africa Clean Energy Corridor. These resources, however, are unevenly spatially distributed between countries (see plots for wind, solar PV, and solar CSP potential in Figure 12, Figure 14, and Figure 15).

More so than other resource assessment criteria such as slope, elevation or land use land cover, the quality of wind resources primarily determined the area of suitable sites for wind generation. In countries with limited wind potential such as Angola, Democratic Republic of Congo, Zambia, Zimbabwe, Malawi, Mozambique, Uganda, Tanzania, and Swaziland, the wind resource areas (Figure 16 for EAPP and Figure 19 for SAPP) closely follow the distribution of areas with economically viable wind power density (see map of wind power density above 200 W/m^2 in Figure 43). In Namibia and parts of South Africa, where wind is abundant and of high-quality, protected areas along the coast restrict the extent of wind resource areas (map of wind power density in Figure 43 vs. wind resource areas in Figure 19). Wind resource areas generally agree with previous studies conducted for South Africa, Kenya, and Ethiopia [DEA and CSIR, 2014]. Including agricultural land in wind resource assessments does not significantly increase potential in most countries (see plot of wind generation potential across ACEC countries on non-agricultural and agricultural lands in Figure 13). However, agricultural land comprises about half the wind resource area in Malawi, Mozambique, Tanzania, and Zimbabwe, and greater than half in Zambia (Figure 13). Because the direct land footprint of a wind turbine is small relative to the entire area of a wind farm [Denholm et al., 2009], dual use of the land for farming and wind generation is not only possible, but preferable from a land use efficiency point of view. Policies such as land-leasing could be important to ensure socially equitable wind development.

Although high-quality solar PV resources exist throughout the ACEC (see map of solar GHI above 230 W/m^2 or 5.5 $kWh/m^2/day$ in Figure 41), the potential is constrained primarily by the type of land use and land cover (LULC), and slope. Solar PV in Ethiopia and Lesotho is largely limited by the hilly terrain (slope between 5% and 20%) covering most of Lesotho and areas close to load centers in central and northern Ethiopia (see map of slope in Figure 44). Although Western Swaziland has sufficient insolation, large parts of the area exceed the 5% slope threshold imposed for solar technologies. Malawi, Mozambique, Zambia, Uganda, Tanzania, and the Democratic Republic of Congo have large areas with land cover unfavorable for solar PV development (see map of land use and land cover in Figure B - 8 and exclusion categories in Table 2), with Malawi facing a combination of high population density and LULC constraints. High population density (Figure 47), hilly terrain (Figure 44), high elevation (Figure 45), and tree-covered or agricultural land cover (Figure 48) constrain the available land for utility-scale solar PV in Burundi and Rwanda, despite having sufficient solar insolation (see map of solar GHI in Figure 41). Thresholds for these exclusion criteria needed to be relaxed in order to identify solar resource areas in Burundi and Rwanda (section 2.9).

Solar CSP resource areas, like wind, are largely dictated by the spatial distribution of the direct normal irradiance (see map of solar DNI above 260 W/m^2 or 6.2 $kWh/m^2/day$ in Figure 42). Several countries either have little (DRC, Mozambique, Uganda) or no resource (Djibouti, Burundi, Rwanda, Swaziland) due to insufficient DNI levels (see the estimated installed capacity potential for CSP in Table 9 and map of solar DNI in Figure 42). The highest quality and most abundant CSP potential exists in Namibia, South Africa, Botswana, and Ethiopia (CSP resource areas in Figure 18 for EAPP and in Figure 21 for SAPP). Lesotho's hilly terrain limits the amount of solar CSP potential.

Readers may use the country-specific interactive PDF maps, which contain layers of all development constraints, to examine the resource assessment exclusions for each country in detail.

TABLE 9: Estimated installed capacity potential[1] (MW) for wind, solar PV, and solar CSP at various thresholds of resource quality.

	Wind					Solar PV					Solar CSP				
W/m²	200	250	300	350	400	230	240	250	260	270	260	270	280	290	300
kWh/m²-d						5.5	5.8	6	6.2	6.5	6.2	6.5	6.7	7	7.2
Angola	280	170	170	170	170	87,300	79,200	65,300	51,500	13,100	24,900	19,700	13,800	8,150	3,280
Botswana	139,000	40,100	2,080	0	0	751,000	751,000	736,000	489,000	42,800	423,000	407,000	379,000	279,000	131,000
Burundi	0	0	0	0	0	1,190	0	0	0	0	0	0	0	0	0
Djibouti	19,600	12,100	4,630	2,950	1,890	33,200	33,200	26,800	4,260	84	0	0	0	0	0
DRC	1,730	460	89	12	0	18,900	16,800	8,520	1,330	160	150	37	0	0	0
Egypt	397,000	97,400	38,300	22,800	15,200	2,080,000	1,308,000	192,000	1,370	0	144,000	38,200	5,640	640	130
Ethiopia	470,000	373,000	298,000	227,000	93,000	780,000	780,000	718,000	540,000	214,000	232,000	163,000	90,700	55,000	28,600
Kenya	360,000	249,000	144,000	58,200	38,700	460,000	446,000	291,000	174,000	71,200	44,700	19,100	4,460	1,680	930
Lesotho	6,850	3,970	2,830	1,880	1,180	4,800	4,800	4,800	170	0	2,640	2,640	2,640	2,640	2,640
Libya	527,000	158,000	56,900	18,200	8,250	4,511,000	3,402,000	1,669,000	133,000	5,520	1,595,000	642,000	52,800	3,470	180
Malawi	6,080	2,330	480	16	0	2,000	1,990	1,570	990	70	640	200	0	0	0
Mozam-bique	52,100	14,000	2,530	440	34	20,300	11,800	3,630	68	0	110	0	0	0	0
Namibia	161,000	80,600	43,800	20,700	7,830	801,000	801,000	800,000	794,000	459,000	454,000	452,000	443,000	412,000	382,000
Rwanda	0	0	0	0	0	4,530	4,530	4,490	79	0	0	0	0	0	0
South Africa	1,098,000	595,000	308,000	176,000	94,600	1,509,000	1,459,000	1,305,000	907,000	37,700	865,000	859,000	837,000	782,000	734,000
Sudan	471,000	137,000	45,900	21,800	14,100	4,071,000	4,053,000	3,596,000	2,292,000	736,000	1,420,000	872,000	282,000	30,300	0
Swaziland[2]	4,430	420	0	0	0	12	0	0	0	0	0	0	0	0	0
Tanzania	46,900	20,800	9,390	4,570	1,900	59,000	59,000	58,400	50,700	47,200	26,100	21,600	10,500	4,140	500
Uganda	2,140	790	350	19	0	11,400	11,400	11,400	11,400	7,100	3,230	1,590	210	0	0
Zambia	32,000	4,770	860	240	0	19,600	19,600	19,600	18,400	690	7,840	5,100	1,620	0	0
Zimbabwe	39,300	5,960	430	0	0	109,000	77,000	62,200	42,300	5,280	39,500	35,100	31,200	19,000	4,350

[1]Please refer to Table 7 for land use and land use discount factors applied to each technology.
[2]Swaziland has approximately 700 MW of solar PV potential above a threshold of 210 W/m².

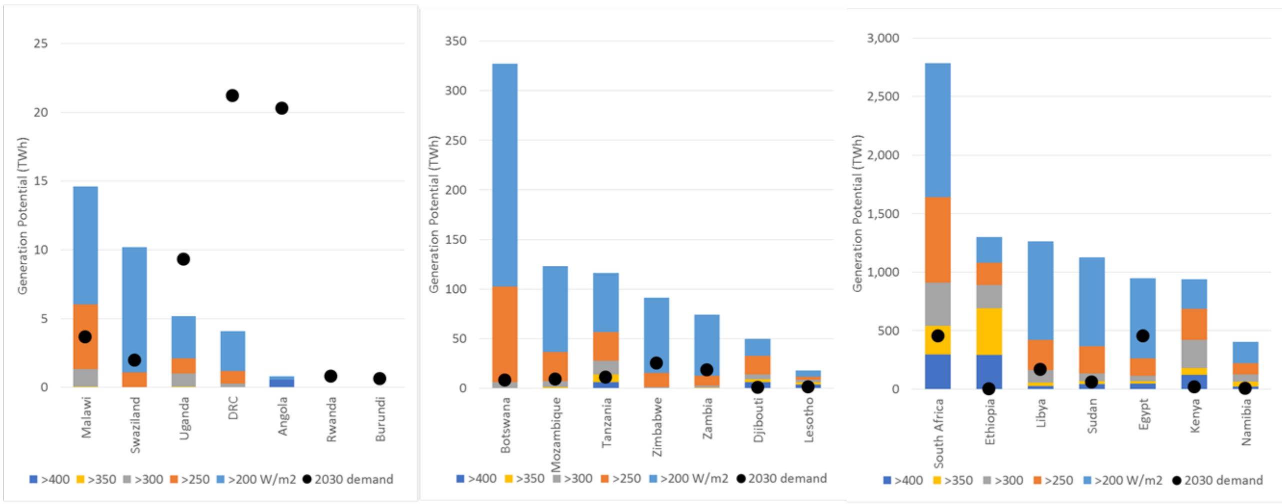


FIGURE 12: Wind generation potential (TWh) across the ACEC.

Wind generation potentials are plotted along three different y-axis scales, since potential values across the ACEC differ by two orders of magnitude. The height of each of the stacked bars shows the amount of generation potential (TWh) above the indicated potential thresholds (W/m²). Each bar is stacked from highest quality resource (bottom) to lowest quality resource (top). The projected 2030 demand for each country reported in the SAPP and EAPP master plans [EAPP et al., 2011] [SAPP and Nexant, 2007] is provided as a reference value for the potential estimates. The land use discount factor assumed for wind generation potential is 25% due to uncertainties associated with actual development.

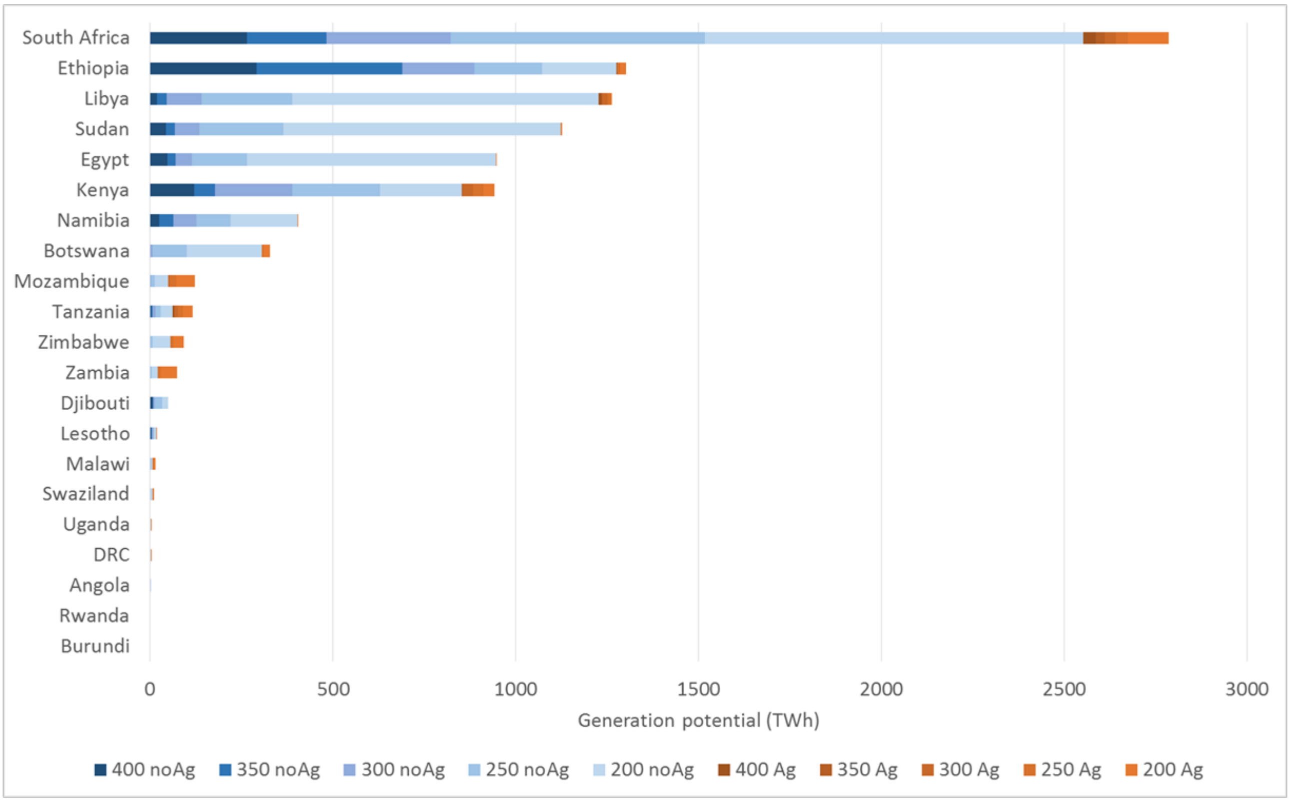


FIGURE 13: Wind generation potential (TWh) across the ACEC on non-agricultural and agricultural lands.

The length of each of the stacked bars show the amount of generation potential above the potential thresholds (W/m^2). Blue bars indicate resource on non-agricultural land and orange bars indicate potential on agricultural land.

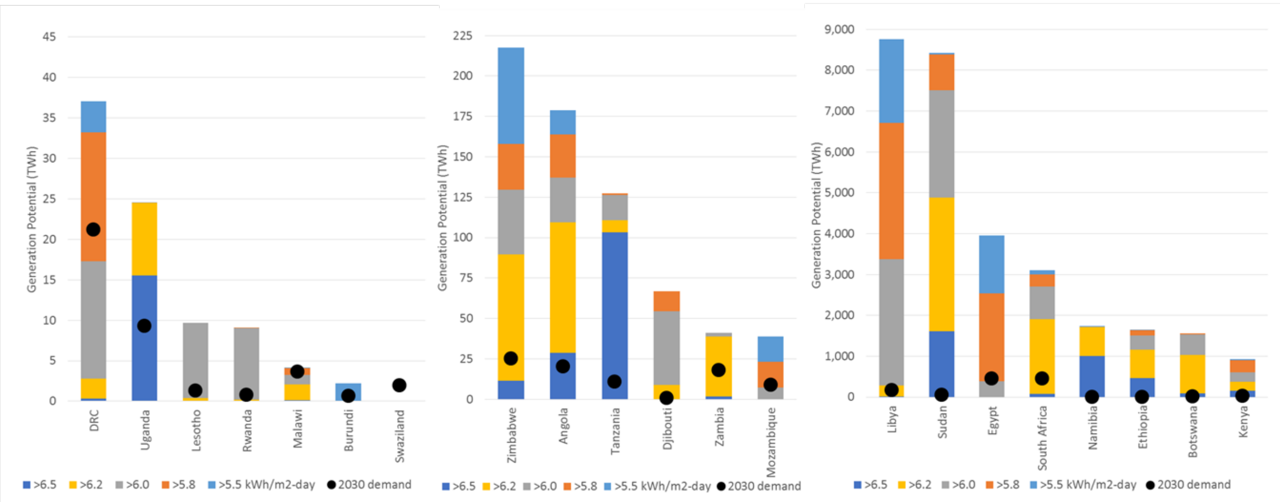


FIGURE 14: Solar PV generation potential (TWh) across the ACEC.

Solar PV generation potentials are plotted along three different y-axis scales, since potential values across the ACEC differ by more than two orders of magnitude. The height of each of the stacked bars shows the amount of generation potential above the indicated potential thresholds (kWh/m^2-day). Each bar is stacked from highest quality resource (bottom) to lowest quality resource (top). The projected 2030 demand for each country reported in the SAPP and EAPP master plans [EAPP et al., 2011] is provided as a reference value for the potential estimates. The land use discount factor assumed for solar PV generation potential is 10% due to uncertainties associated with actual development.

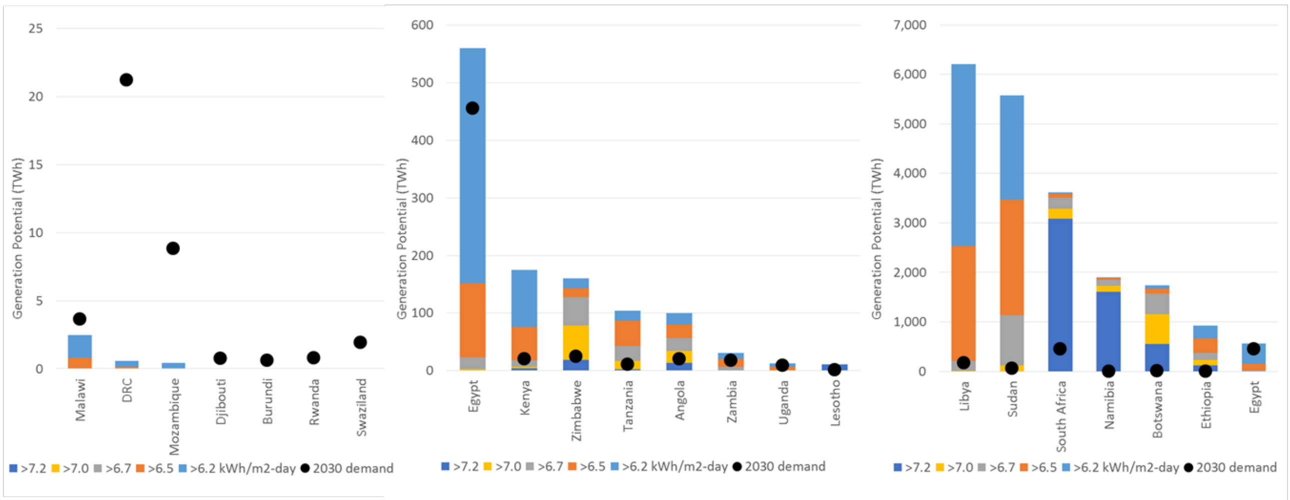


FIGURE 15: Solar CSP generation potential (TWh) across the ACEC.

Solar CSP generation potentials are plotted along three different y-axis scales, since potential values across the ACEC differ by three orders of magnitude. The height of each of the stacked bars shows the amount of generation potential above the indicated potential thresholds (kWh/m^2-day). Each bar is stacked from highest quality resource (bottom) to lowest quality resource (top). The projected 2030 demand for each country reported in the SAPP and EAPP master plans [EAPP et al., 2011] is provided as a reference value for the potential estimates. The land use discount factor assumed for solar CSP generation potential is 10% due to uncertainties associated with actual development.

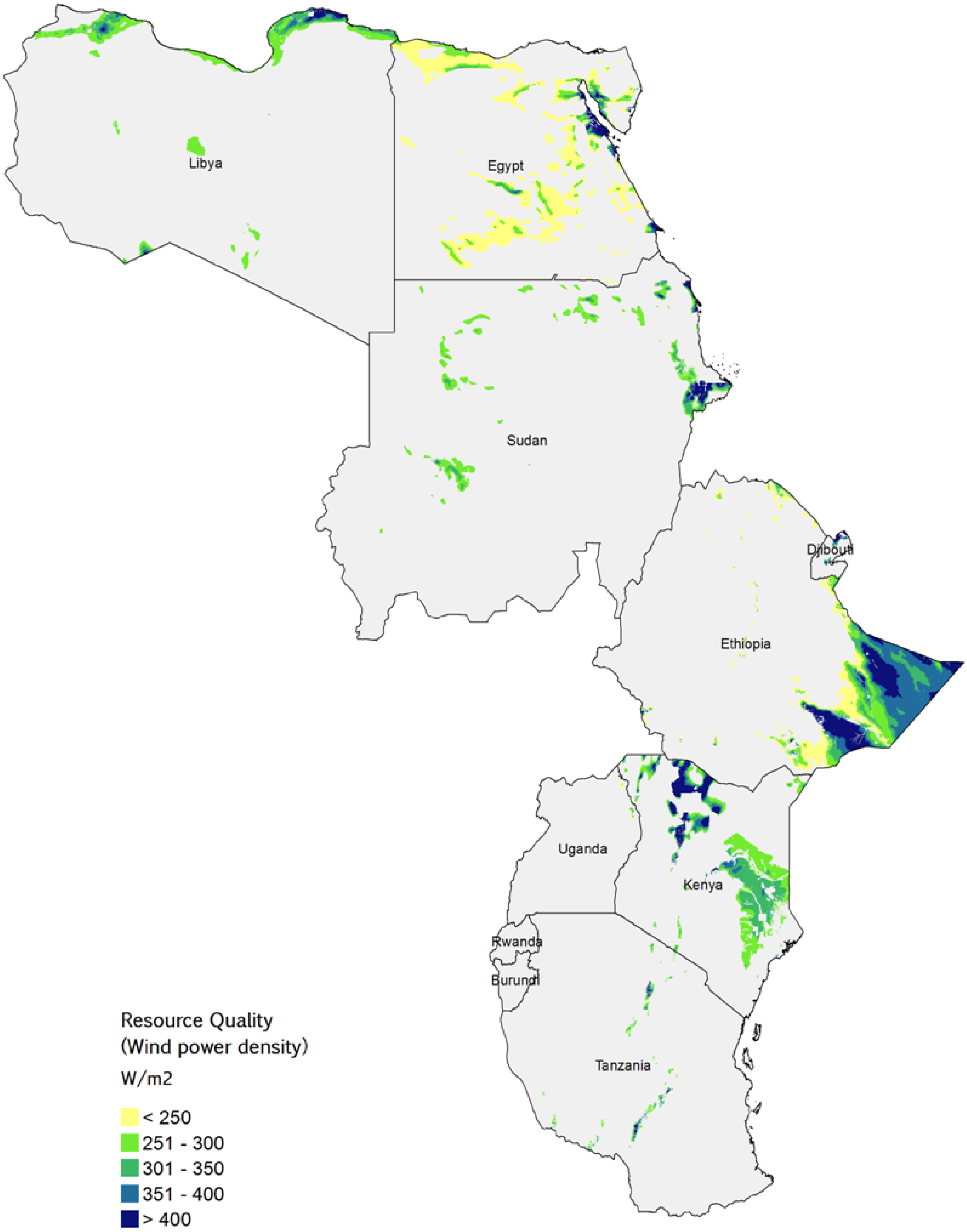


FIGURE 16: Wind power density of resource areas in the Eastern Africa Power Pool (EAPP).

Resource quality thresholds vary from 200 W/m^2 (5.6 m/s) to 300 W/m^2 (6.4 m/s) for different countries as described in Table 3

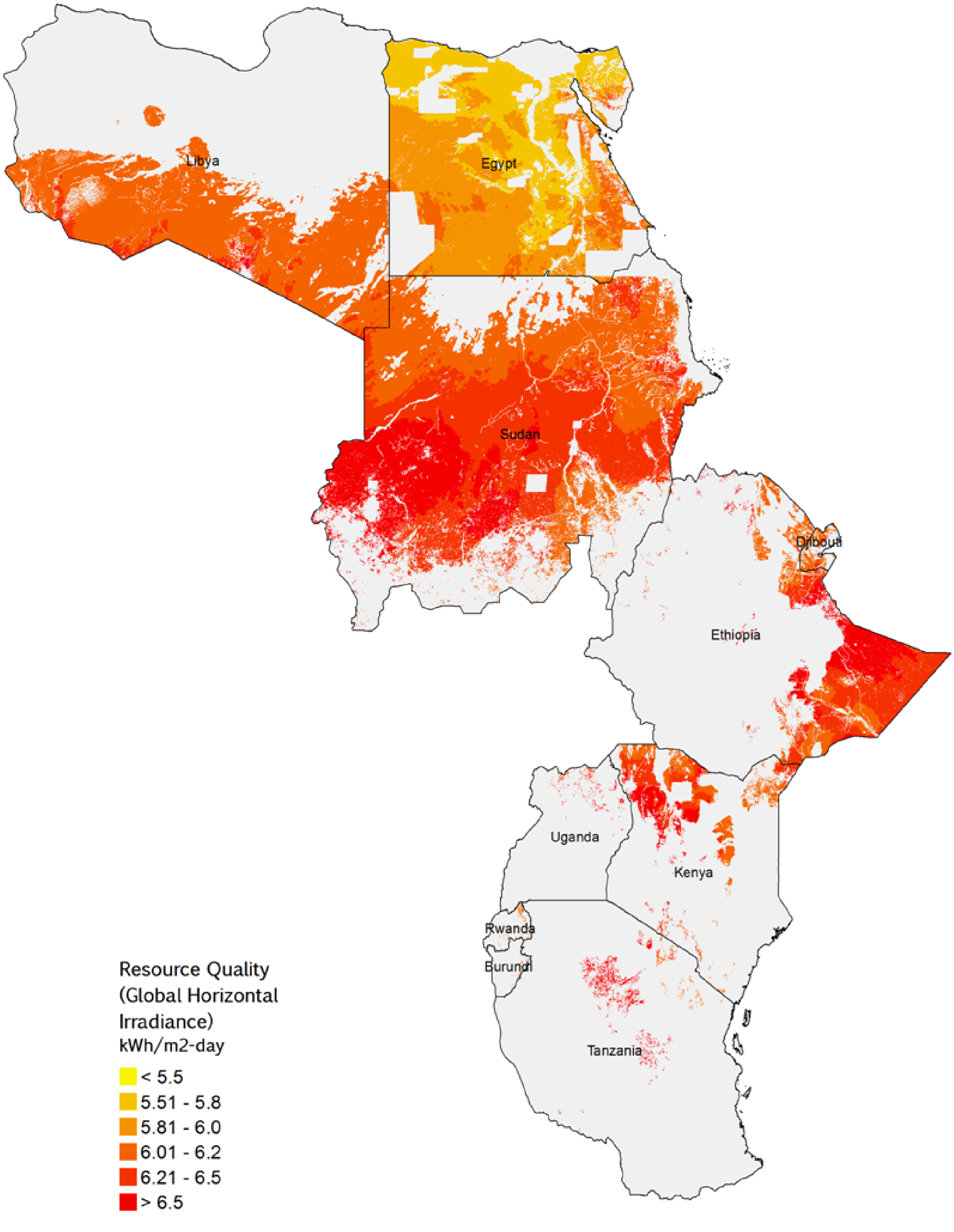


FIGURE 17: Global horizontal irradiance of solar PV resource areas in the Eastern Africa Power Pool (EAPP).

Resource quality thresholds vary from 230 W/m^2 (5.5 kWh/m^2/day) to 250 W/m^2 (6 kWh/m^2/day) for different countries as described in Table 3

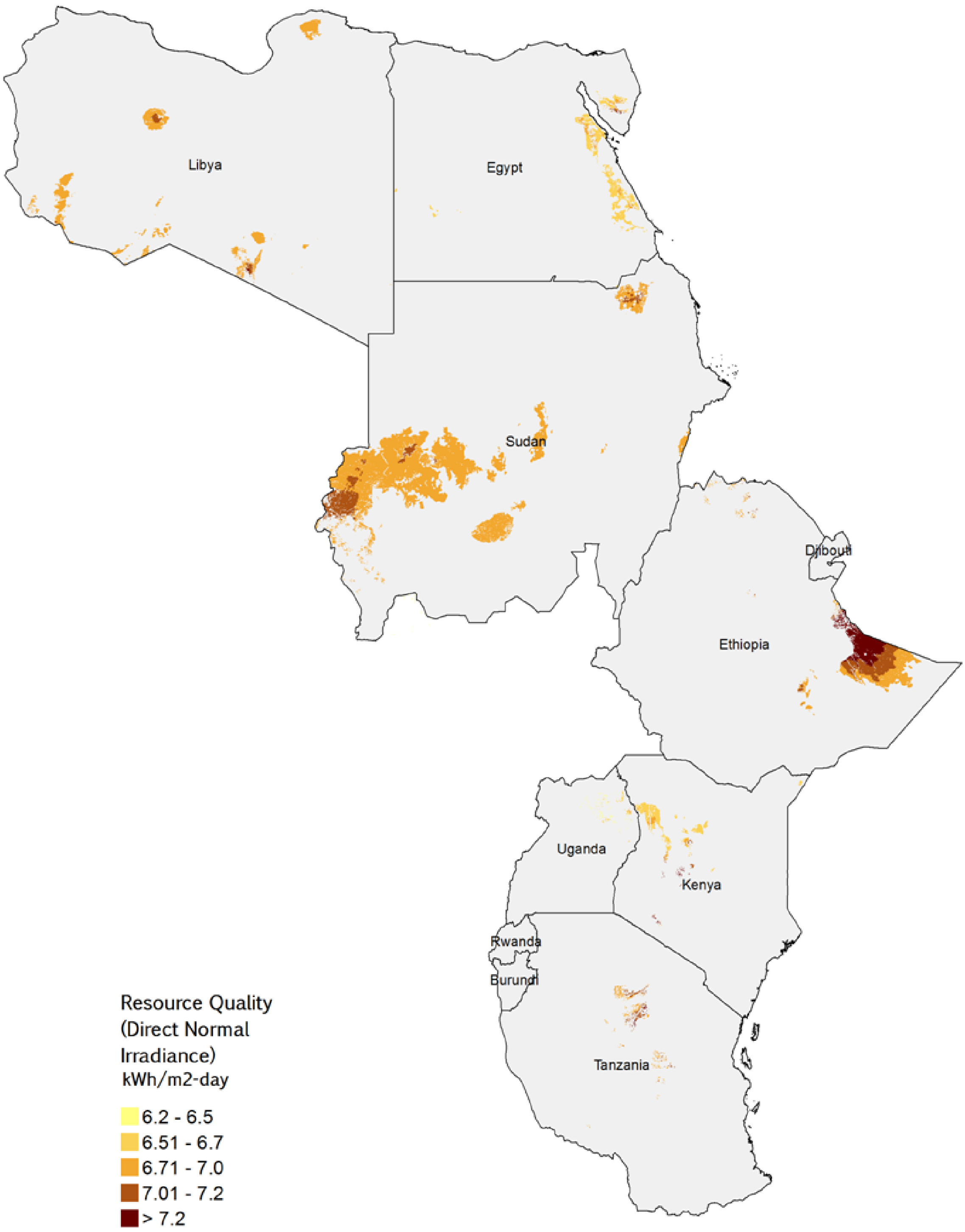


FIGURE 18: Direct normal irradiance of solar CSP resource areas in the Eastern Africa Power Pool (EAPP).

Resource quality thresholds vary from 260 W/m^2 (6.2 kWh/m^2-day) to 280 W/m^2 (6.7 kWh/m^2-day) for different countries as described in Table 3

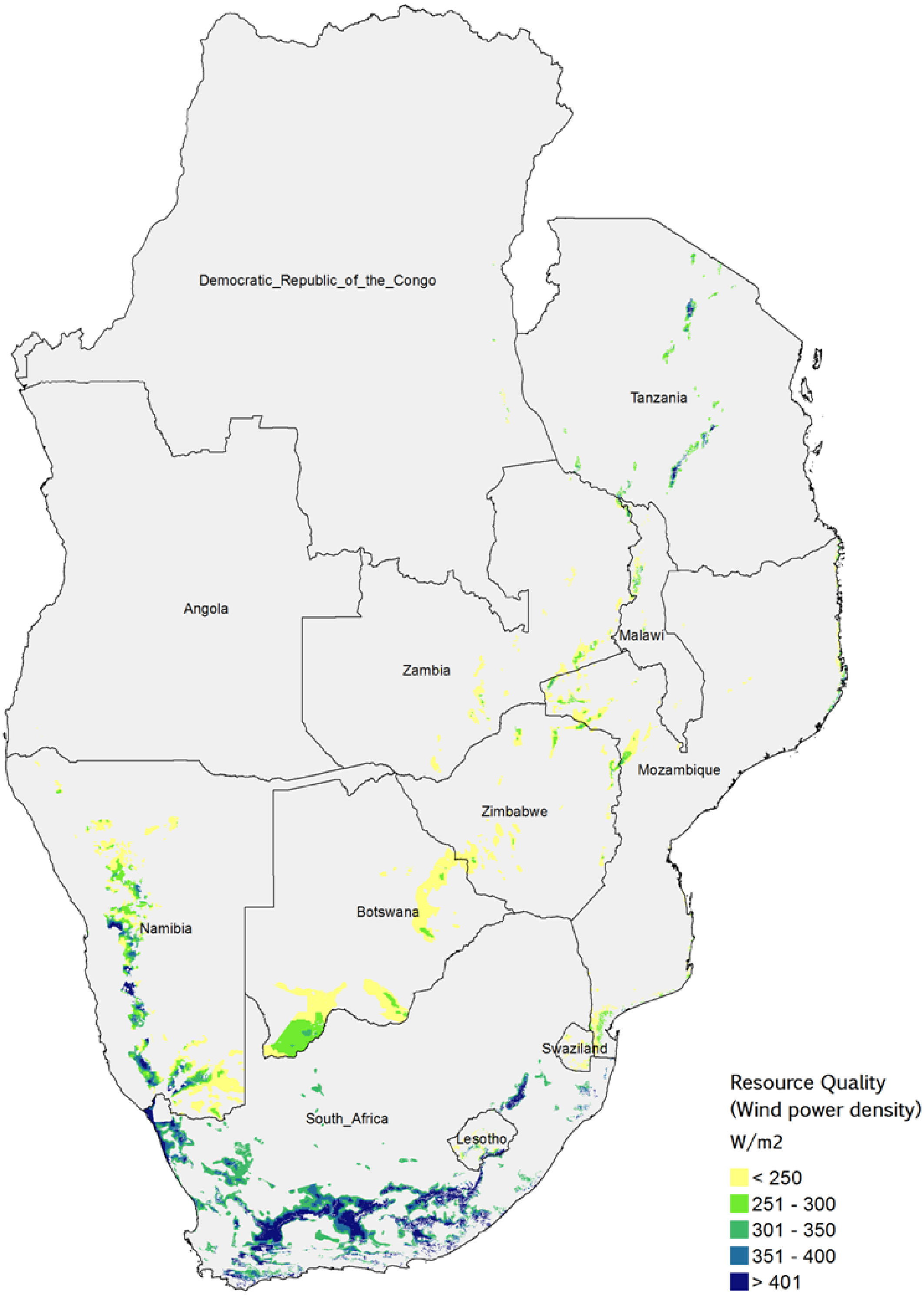


FIGURE 19: Wind power density of wind resource areas in the Southern Africa Power Pool (SAPP).

Resource quality thresholds vary from 200 W/m^2 (5.6 m/s) to 300 W/m^2 (6.4 m/s) for different countries as described in Table 3

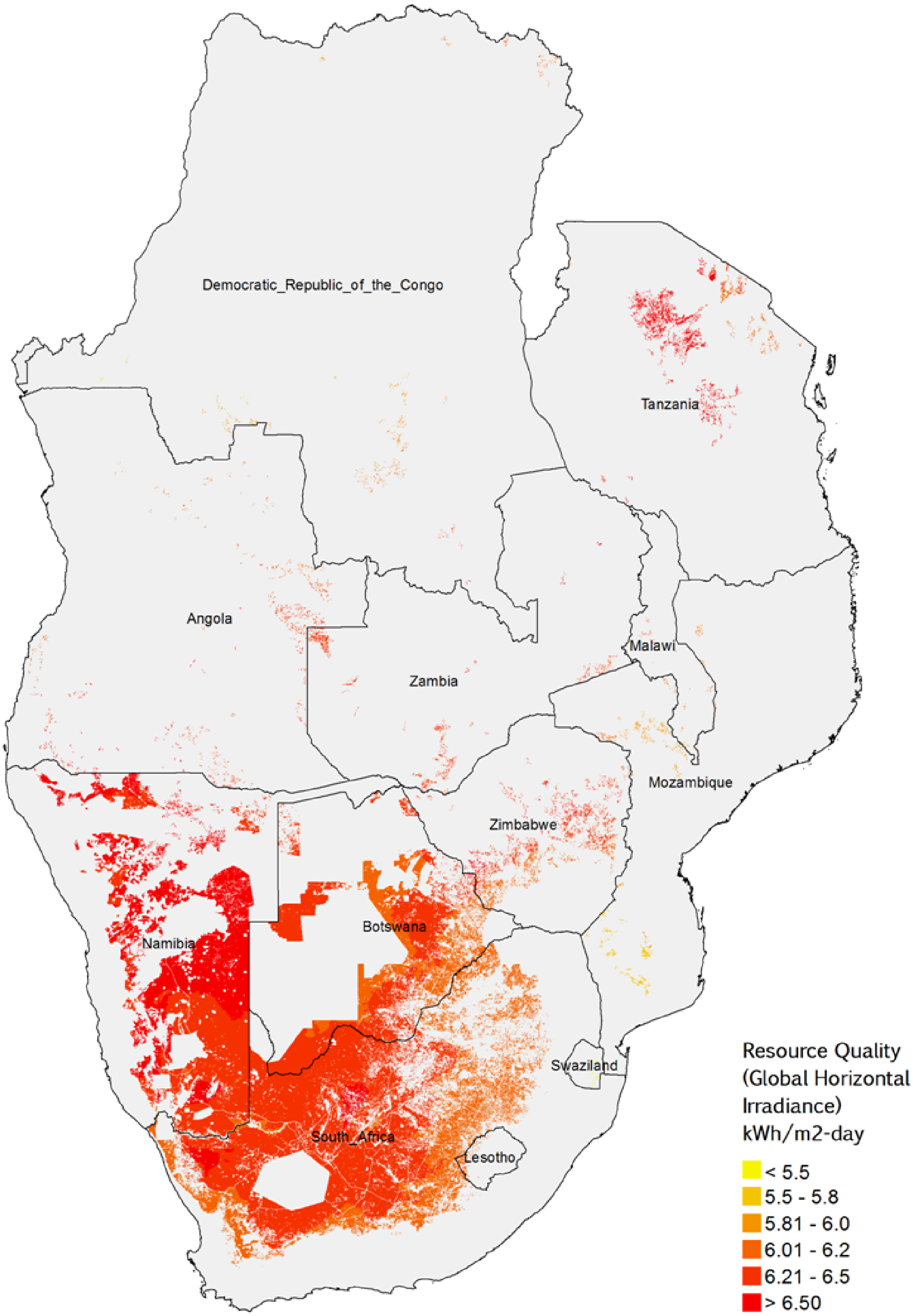


FIGURE 20: Global horizontal irradiance of solar PV resource areas in the Southern Africa Power Pool (SAPP).

Resource quality thresholds vary from 230 W/m^2 (5.5 kWh/m^2-day) to 250 W/m^2 (6 kWh/m^2-day) for different countries as described in Table 3

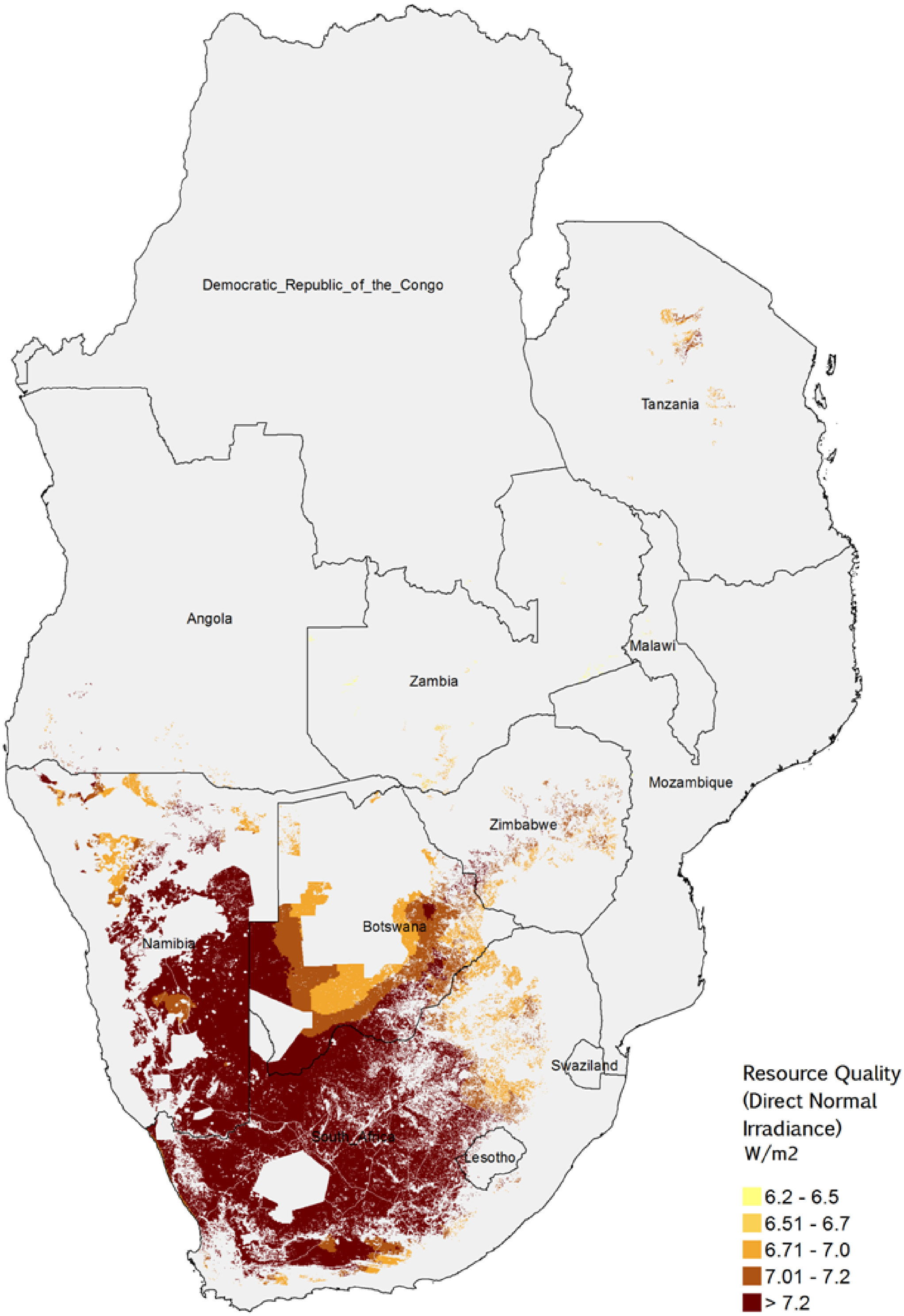


FIGURE 21: Direct normal irradiance of solar CSP resource areas in the Southern Africa Power Pool (SAPP).

Resource quality thresholds vary from 260 W/m^2 (6.2 kWh/m^2/day) to 280 W/m^2 (6.7 kWh/m^2/day) for different countries as described in Table 3

3.2 SPATIAL PATTERNS OF ZONE ATTRIBUTES ACROSS THE AFRICA CLEAN ENERGY CORRIDOR

3.2.1 WIND CAPACITY VALUE

Estimates of wind capacity value demonstrate that wind speed profiles of some wind zones are better matched with peak demand, and that consideration of capacity value could considerably alter the geographic distribution of the most favorable wind zones in the ACEC. The 24-hour histograms of the top 10% of peak hours in a year show that most countries have distinct peak hours during the evening; Sudan's mid-day peak is the only exception (Figure 22). It is important to note that because many countries in this study are capacity-constrained, demand histograms in Figure 22 also reflect possible scheduled and unscheduled curtailment, which may increase the uniformity of the histograms. This means that the top peak hours across a year are distributed across more hours of a day, as opposed to a few. As a result, we estimated capacity value using the following two approaches: 1) using the top 10% of annual demand hours, and 2) using the daily top three peak hours (e.g., 5 – 8 pm) throughout a year (see section 2.7 for detailed descriptions of metric calculations and Table 10 for the assumed daily top three peak hours for each country). By choosing proxy daily peak hours for each power pool, the latter approach also enabled the estimation of capacity value for countries with missing demand data (e.g., Egypt, Lesotho).

We compared the capacity value ratios estimated using these two approaches across the ACEC (Figure 23). The differences observed between these two metrics for the same wind zones are likely due to the relative uniformity of the demand histogram. The higher capacity value ratios for the top three daily peak hours compared to the top 10% of peak hours suggests that peak wind power output consistently occurs during the evening peak hours (Figure 23). Differences between the two metrics can be observed for wind zones in Ethiopia, Namibia, South Africa, Swaziland, Tanzania, and Zimbabwe. A capacity value ratio greater than 1 indicates that the capacity factor during the top three or 10% peak hours is higher than the annual average capacity factor. A subset of zones in all countries within the ACEC have capacity value ratios greater than 1 (Figure 23), suggesting that the development of these specific wind zones within a country may be more favorable from a grid reliability standpoint.

To select zones with a combination of peak demand matching (capacity value ratio) and high absolute generation (capacity factor), capacity values must be estimated. This was accomplished by simply multiplying the capacity value ratio with the average annual capacity factor (Figure 24, Figure 25). For example, these adjusted capacity factors, or capacity values, show that wind in the Eastern Cape in South Africa is about 20% higher during the top 10% of peak hours (Figure 24) and wind in the Northern Cape is consistently stronger during the evening peak hours (Figure 26). Zones in northern Egypt, eastern Kenya, Tanzania, central Ethiopia, Zambia, Namibia, and Mozambique that have lower wind quality (<30% annual average CF), show dramatically higher capacity factors during peak hours (>40% capacity value), and importantly, become comparable and competitive with zones in northern Kenya, eastern Sudan, eastern Egypt, and coastal South Africa, which have the best annual average wind capacity factors in the ACEC (Figure 24, Figure 25).

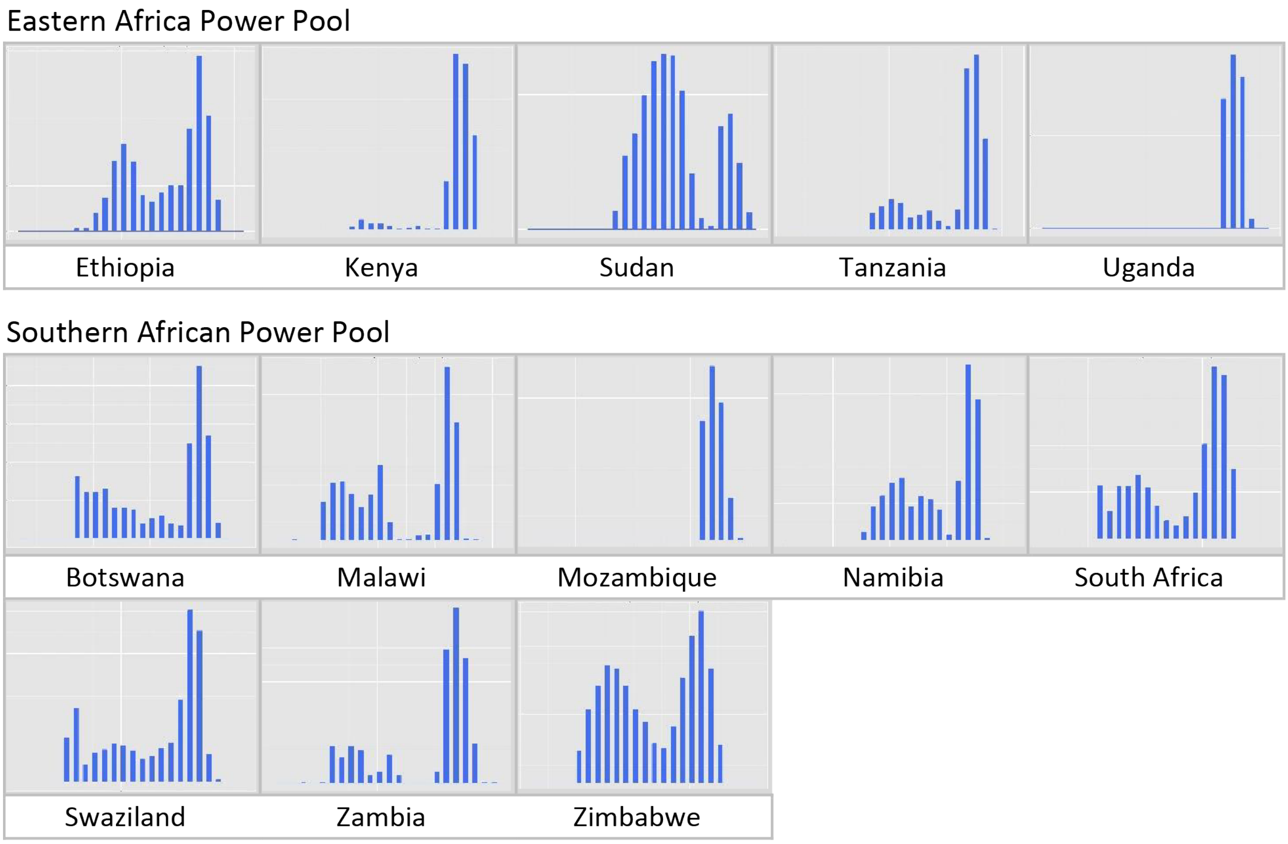


FIGURE 22: Hourly demand histograms for the top 10% of demand hours.

These histograms show the frequency that a particular hour within a day (1 - 24, from left to right along x-axis) occurred in the top 10% of demand hours within a year.

TABLE 10: Criteria value ranges and scores

	Daily top three peak hours		Daily top three peak hours
Angola	19, 20, 21:00 hours	Mozambique	19, 20, 21:00 hours
Botswana	19, 20, 21:00 hours	Namibia	19, 20, 21:00 hours
Burundi	-	Rwanda	-
Djibouti	20, 21, 22:00 hours	South Africa	18, 19, 20:00 hours
DRC	19, 20, 21:00 hours	Sudan	14, 15, 16:00 hours
Egypt	20, 21, 22:00 hours	Swaziland	18, 19, 20:00 hours
Ethiopia	11, 12, 13:00 hours	Tanzania	20, 21, 22:00 hours
Kenya	20, 21, 22:00 hours	Uganda	20, 21, 22:00 hours
Lesotho	18, 19, 20:00 hours	Zambia	19, 20, 21:00 hours
Libya	-	Zimbabwe	18, 19, 20:00 hours
Malawi	18, 19, 20:00 hours		

Daily top three peak hours for countries missing demand data were chosen using neighboring countries' peak hours. Wind capacity values were not estimated for Rwanda and Burundi due to lack of wind resources above assumed thresholds, and for Libya where zones were not processed.

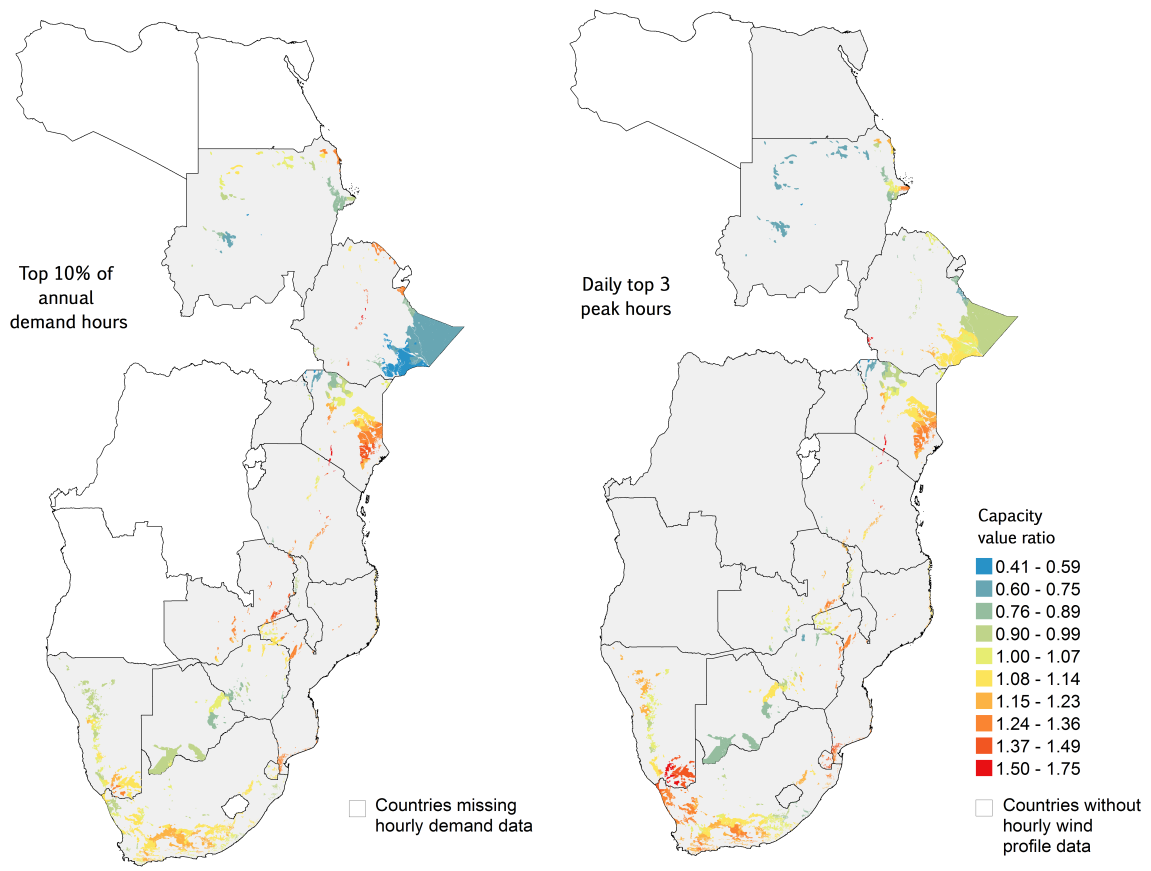


FIGURE 23: Comparison of capacity value ratios for ACEC wind zones.

Ratios were estimated using (A) the top 10% of demand hours within the years of demand data provided and (B) the top three hours within a day, estimated over 10 years. Zones for Libya were not processed.

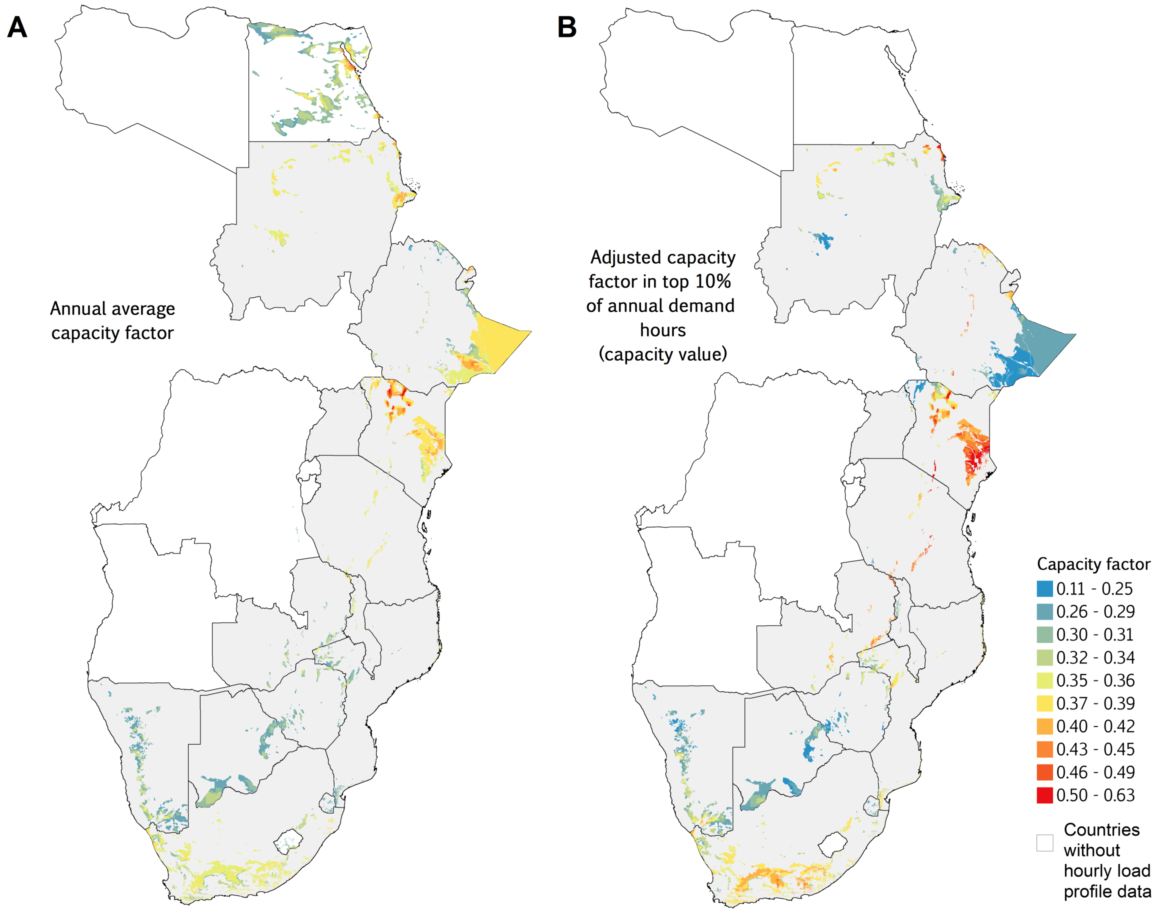


FIGURE 24: Comparison of annual average capacity factor (A) with 10% peak hour adjusted capacity factor (capacity value) (B) for ACEC wind zones

Adjusted capacity factors for the top 10% peak hours were not calculated for Egypt, Djibouti, DRC, Angola, and Lesotho because of lack of demand data. No significant wind resources were identified in Burundi and Rwanda. Zones for Libya were not processed.

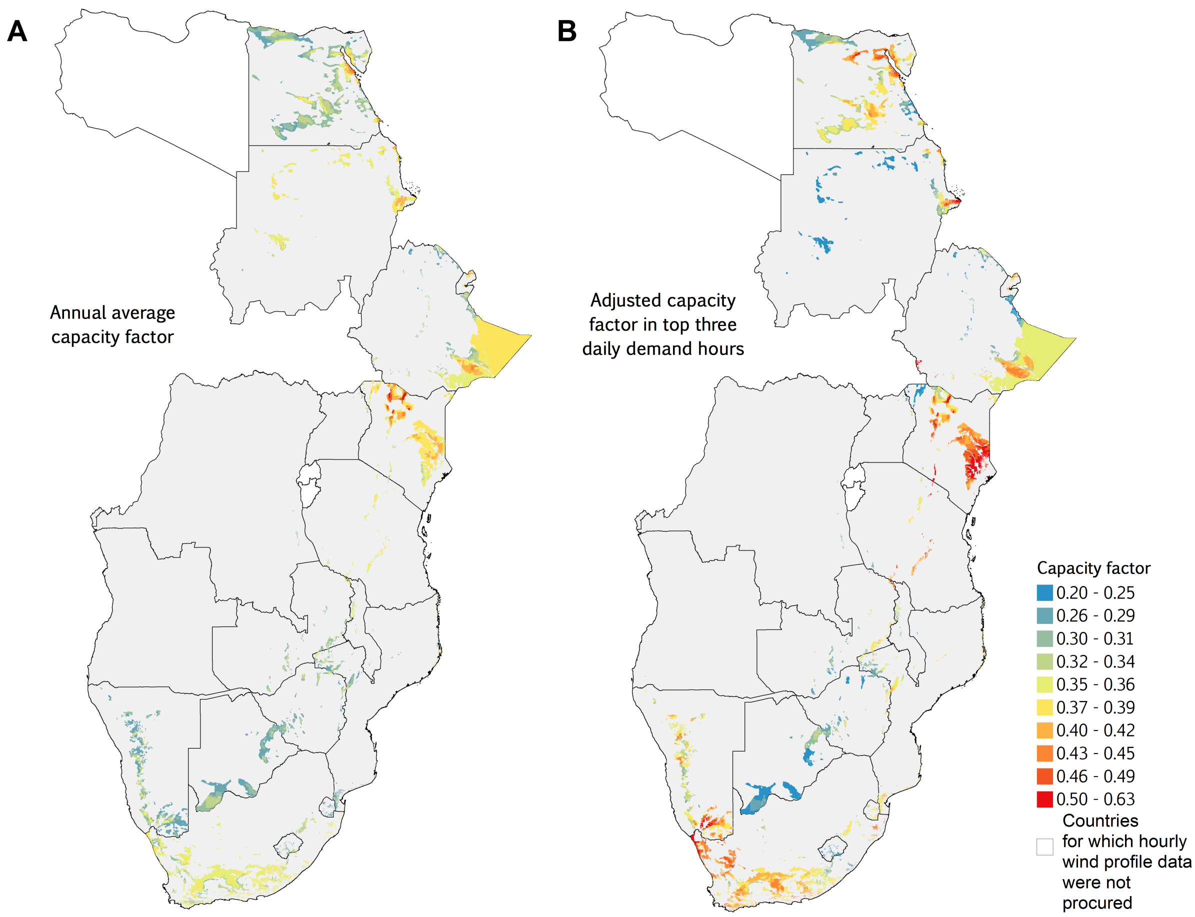


FIGURE 25: Comparison of annual average capacity factor (A) with adjusted capacity factor for daily top three peak hours (capacity value) (B) for ACEC wind zones.

The daily top three peak demand hours for Egypt, Djibouti, DRC, Angola, and Lesotho were assumed based on demand data from neighboring countries. Zones for Libya were not processed.

3.2.2 HUMAN FOOTPRINT

Large areas of low cost wind, solar PV, and solar CSP zones are located in areas with both low and high human disturbance (Figure 26 - Figure 28). Therefore, high-environmental-impact development will need to be actively avoided. Due to lack of ACEC-wide spatial data on the environmental value of non-protected land, we used a human disturbance metric as a proxy for ecological intactness and value (see section 2.5.5 for detailed calculation of the human footprint metric). Comparisons of total LCOE and human footprint score, combined with capacity value considerations (Figure 24, Figure 25), show many wind zones in the Eastern Cape of South Africa, Zimbabwe, Mozambique, Zambia, Malawi, Tanzania, southern Kenya, central Ethiopia, eastern Sudan, and eastern Egypt that can be developed cost-effectively in areas that have significant human disturbance (Figure 26). Many of these same countries, in addition to Rwanda, Burundi, Lesotho, and Uganda, can pursue low-impact, cost-effective development of solar PV zones (Figure 27). A subset of these countries can also select low impact areas to develop solar CSP (Figure 28). Thus, developers and policy makers should consider not only the lowest LCOE sites, but also aim to minimize the environmental impact of development.

3.2.3 DISTANCE TO LOAD ENTERS AND TRANSMISSION INFRASTRUCTURE

Although long distance transmission extensions may not result in significant LCOE estimate increases, in actuality, new transmission extensions are often expensive, difficult to site due to social and environmental concerns, and require many years of planning and construction. As such, siting new renewable energy power plants far from transmission infrastructure not only necessitates additional land use, it also stands in the way of cost-efficient and rapid renewable energy deployment. This study is limited in only considering transmission costs of connecting to the nearest existing or planned transmission line or substation and not the subsequent upgrades to other parts of the transmission system that may be needed to deliver electricity to load centers. However, the combination of minimizing distance to transmission infrastructure and load centers reduces these possible upgrade costs, transmission losses, and environmental impacts. The commitment or completion time frame of "planned" transmission lines or substations may vary between countries. As a result, representativeness of each zone's estimated transmission costs and total LCOE depends on each country's commitments to future transmission plans.

An examination of wind, solar PV, and solar CSP zones showed that many zones within 20 km of existing or planned transmission infrastructure, as well as load centers (Figure 29 - Figure 31) are also favorable in terms of their capacity value (Figure 26) and environmental impact (Figure 26 - Figure 28). For example, many wind zones in Tanzania are within 20 km of existing transmission and load centers, have capacity values greater than 0.4, and have human footprint scores greater than 30 (a higher human footprint score indicates more impacted by human activity and thus less pristine lands)

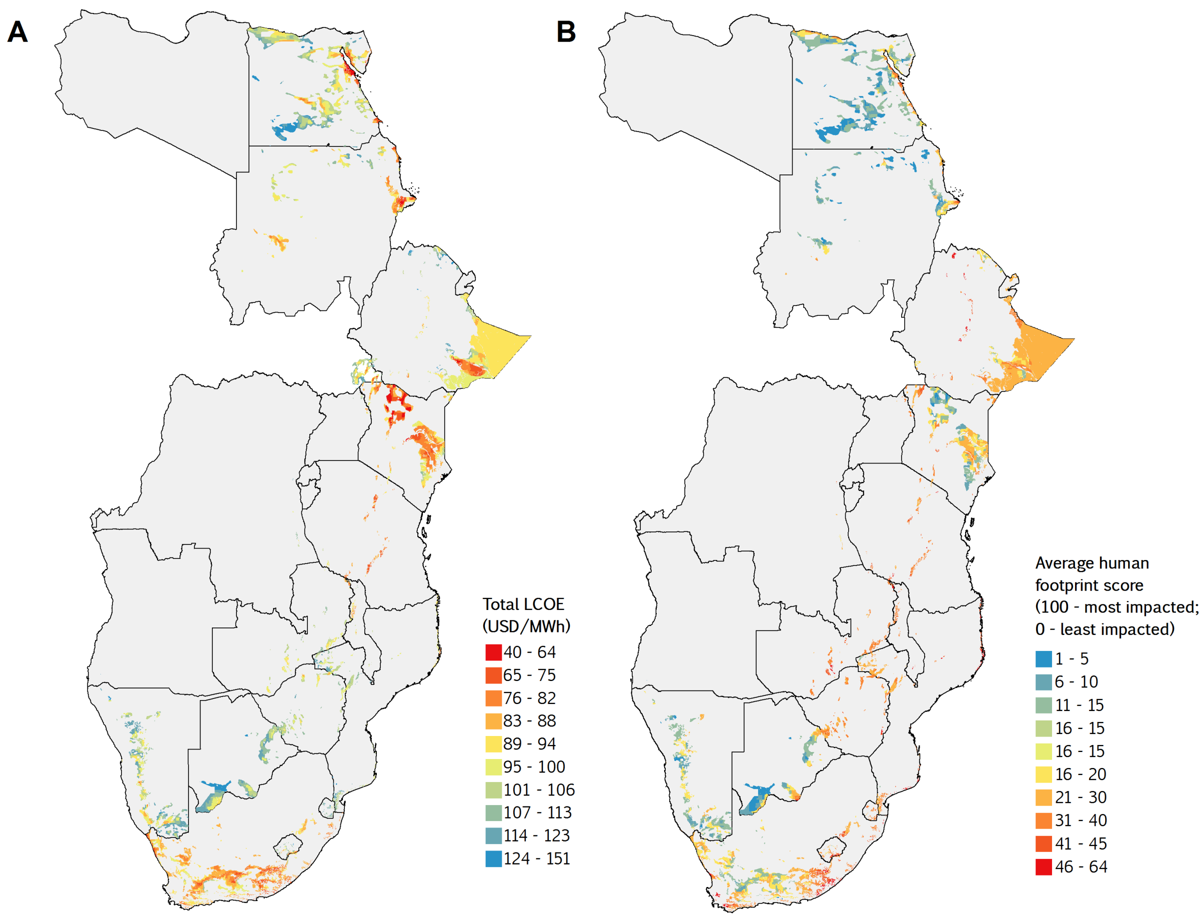


FIGURE 26: Comparison of total levelized cost of energy (LCOE) (A) and human footprint score (B) for wind zones.

Assumptions for estimating LCOE are the same across all countries for comparison purposes. Differences in total LCOE are due to resource quality, and distances to transmission infrastructure and roads. Zones for Libya were not processed. Areas that are red are preferred.

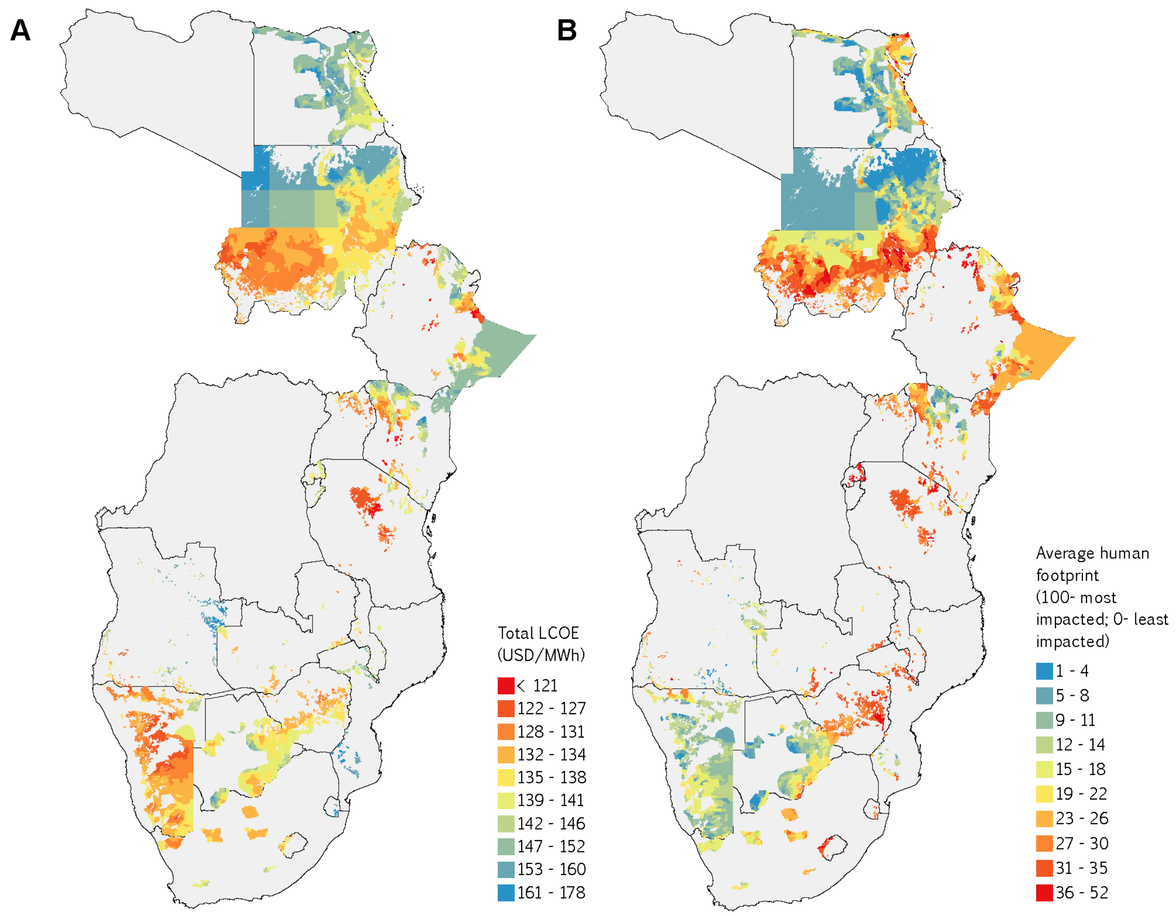


FIGURE 27: Comparison of total levelized cost of energy (LCOE) (A) and human footprint score (B) for solar PV zones.

Due to its large solar PV potential, South Africa's analysis is restricted to the renewable energy development focus areas already identified [DEA and CSIR, 2014]. Some zones in Sudan that are far from transmission infrastructure were processed as large square areas. Assumptions for estimating LCOE are the same across all countries for comparison purposes. Differences in total LCOE are due to resource quality, and distances to transmission infrastructure and roads. Zones for Libya were not processed. Areas that are red are preferred.

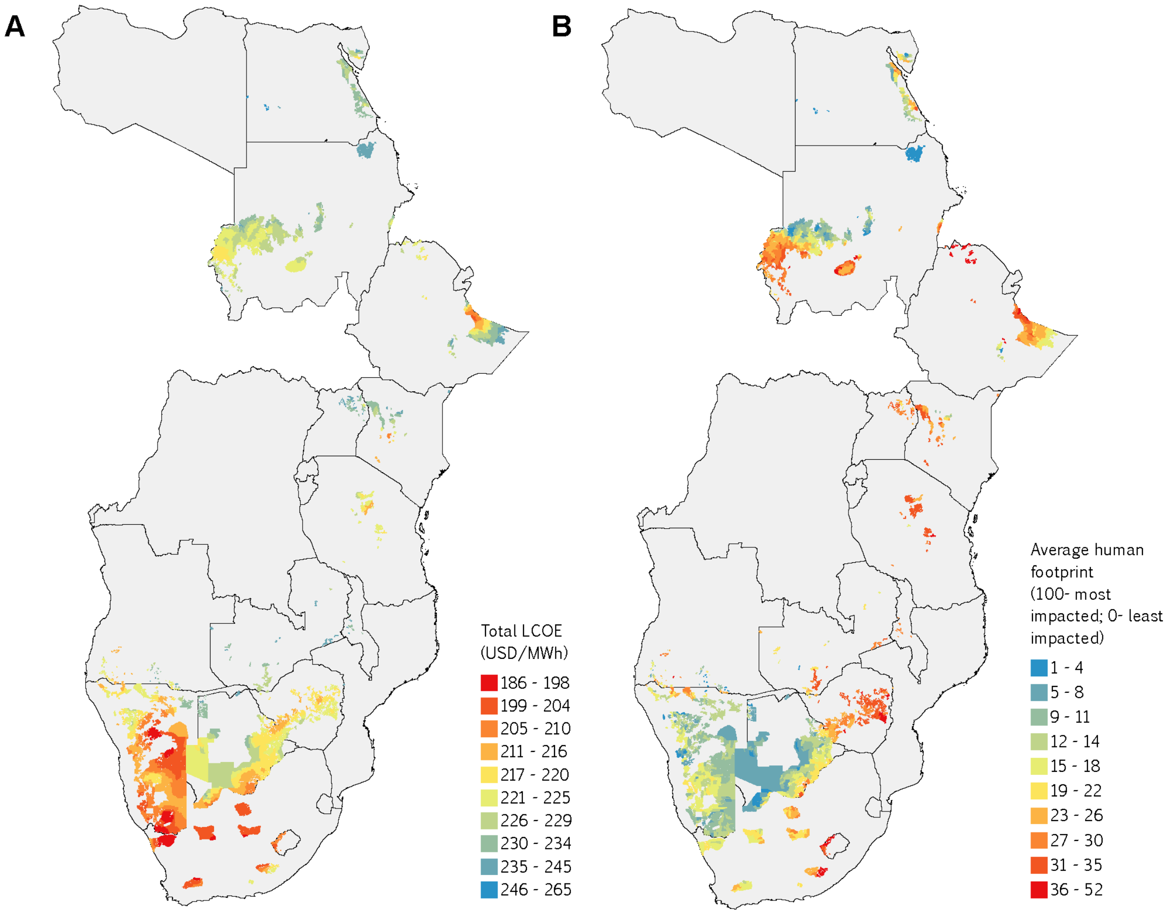


FIGURE 28: Comparison of total levelized cost of energy (LCOE) (A) and human footprint score (B) for solar CSP zones.

Due to its large solar CSP potential, South Africa's analysis is restricted to the renewable energy development focus areas already identified [DEA and CSIR, 2014]. Assumptions for estimating LCOE are the same across all countries for comparison purposes. Differences in total LCOE are due to resource quality, and distances to transmission infrastructure and roads. Zones for Libya were not processed. Areas that are red are preferred.

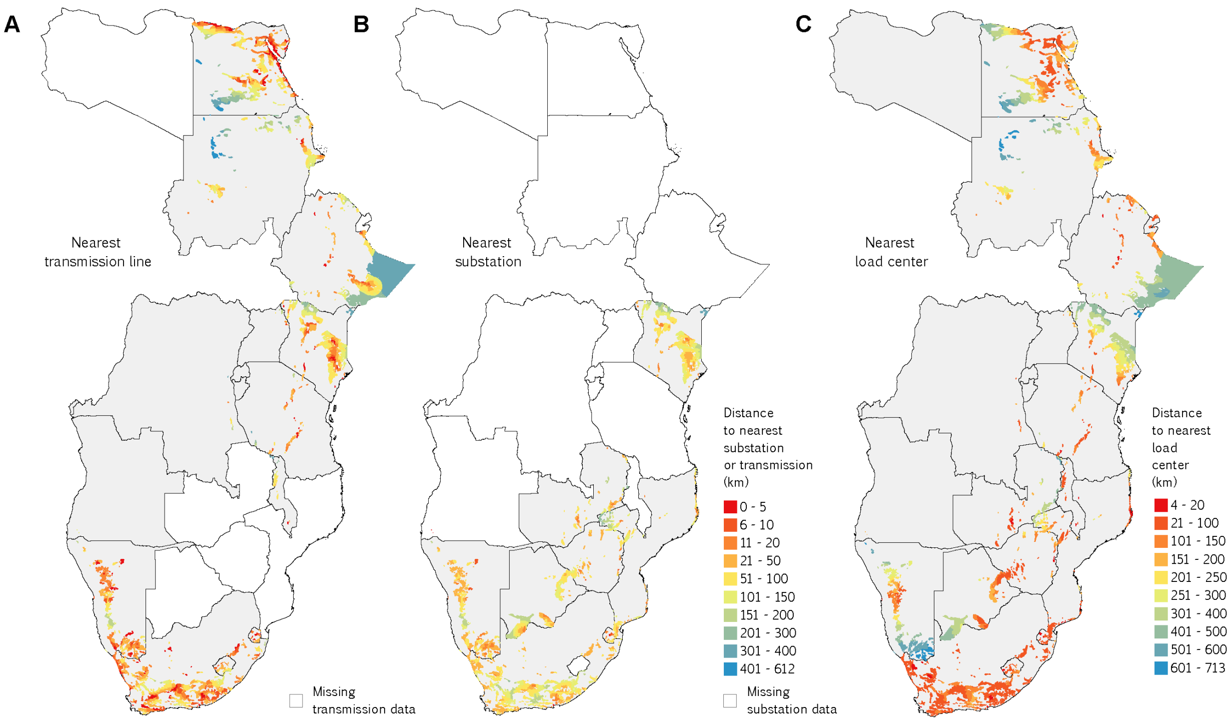


FIGURE 29: Comparison of distance to nearest transmission (A) and substation (B) with distance to nearest load center (C) for wind zones.

Zones for Libya were not processed.

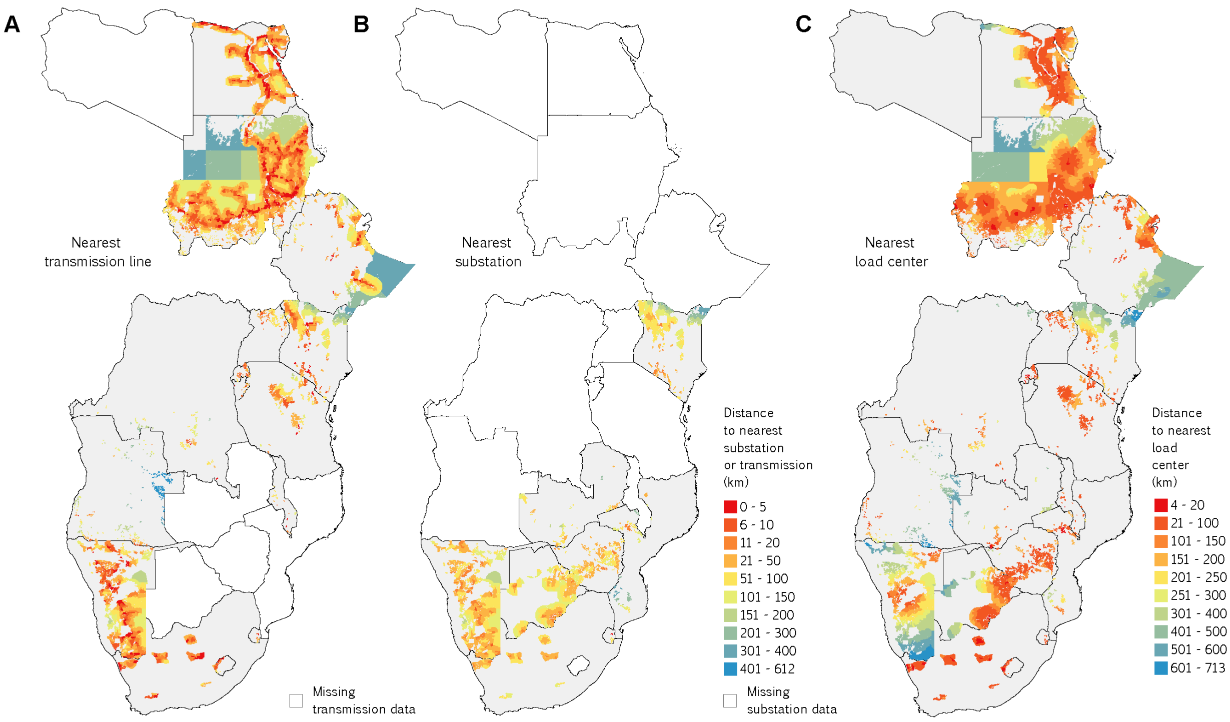


FIGURE 30: Comparison of distance to nearest transmission (A) and substation (B) with distance to nearest load center (C) for solar PV zones.

Due to its large solar PV potential, South Africa's analysis is restricted to the renewable energy development focus areas already identified (Department of Environmental Affairs and Council for [DEA and CSIR, 2014]. Some zones in Sudan that are far from transmission infrastructure were processed as large square areas. Zones for Libya were not processed.

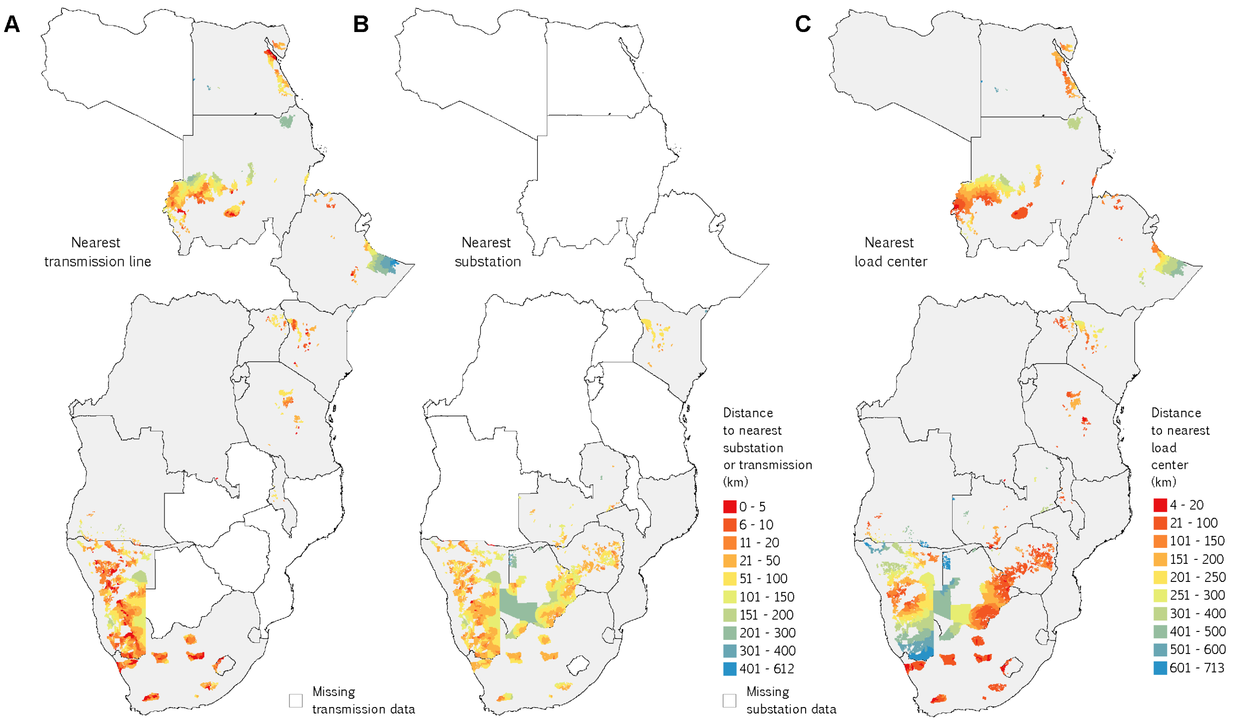


FIGURE 31: Comparison of distance to nearest transmission (A) and substation (B) with distance to nearest load center (C) for solar CSP zones.

Due to its large solar CSP potential, South Africa's analysis is restricted to the renewable energy development focus areas already identified [DEA and CSIR, 2014]. Zones for Libya were not processed.

3.2.4 CO-LOCATION AND PROXIMITY TO GEOTHERMAL PROJECTS

Co-location. The co-location score measures the suitability of an area of land for the development of more than one generation technology. Co-location could be an important siting strategy that minimizes land use, maximizes utilization of transmission capacity, and increases return on investment [Wu et al., 2014]. Efficiently designed co-located wind-PV power plants could double electricity generated on a given area, with shading from turbines resulting in a loss of only 1-2% of total PV production, and have better economies than one technology alone ([SolarPraxis and Reiner Lemoine Institute, 2013]. Because transmission capacity and land can be shared, co-location can minimize transmission and substation land use, reduce right-of-way challenges, and lower permitting costs per MWh produced. Additionally, the seasonal and diurnal complementarity of wind and solar generation profiles would increase utilization of transmission capacity [Sioshansi and Denholm, 2013]. However, co-location of solar projects with wind projects will limit the latter's ability to utilize its land for other purposes such as agriculture.

In Figure 32, all wind zones with scores greater than zero suggest that at least one project opportunity area within the zone is suitable for development of solar PV. The closer the score is to 0.5, the more project opportunity areas within the zone are suitable for both wind and solar PV. The closer the score is to 1, the more a zone is suitable for wind, solar PV, and solar CSP. Nearly all wind zones in Namibia and Botswana are favorable for solar PV development, with the vast majority of those zones also favorable for solar CSP development (Figure 32). A large fraction of wind zones in South Africa, Zimbabwe, Tanzania, Kenya, Sudan, and Egypt, can be co-located with solar PV.

Geothermal projects. As with co-location of solar and wind projects, prioritizing wind and solar zones overlapping with or in close proximity to geothermal projects may reduce investment risk and maximize infrastructure efficiency through sharing of transmission infrastructure. Several solar PV zones within Kenya, Ethiopia, Djibouti, and Mozambique fall within 25 km of an existing or potential geothermal project (Figure 33A). Wind zones within 25 km of geothermal projects can be found in Sudan, Ethiopia, Djibouti, Kenya, and Malawi (Figure 33B).

3.2.5 WATER AVAILABILITY

Although new solar CSP plants have begun to adopt dry cooling technologies, where water is readily, affordably, and sustainably available, wet-cooling is still the most cost-effective option. Many solar CSP zones in Namibia, Botswana, South Africa, Zimbabwe, Lesotho, and Tanzania have more than 10 project opportunity areas within 10 km of surface water (rivers, lakes, reservoirs) (Figure 34). A few zones in northern Ethiopia, central Kenya, northern Zambia, Malawi, have access to water. Although we have not presented the results here, we have calculated the same water availability metric for solar PV zones, since solar PV plants generally require water for washing panels [Macknick et al., 2011]. The newest PV array designs incorporating automated cleaning can drastically reduce water consumption.

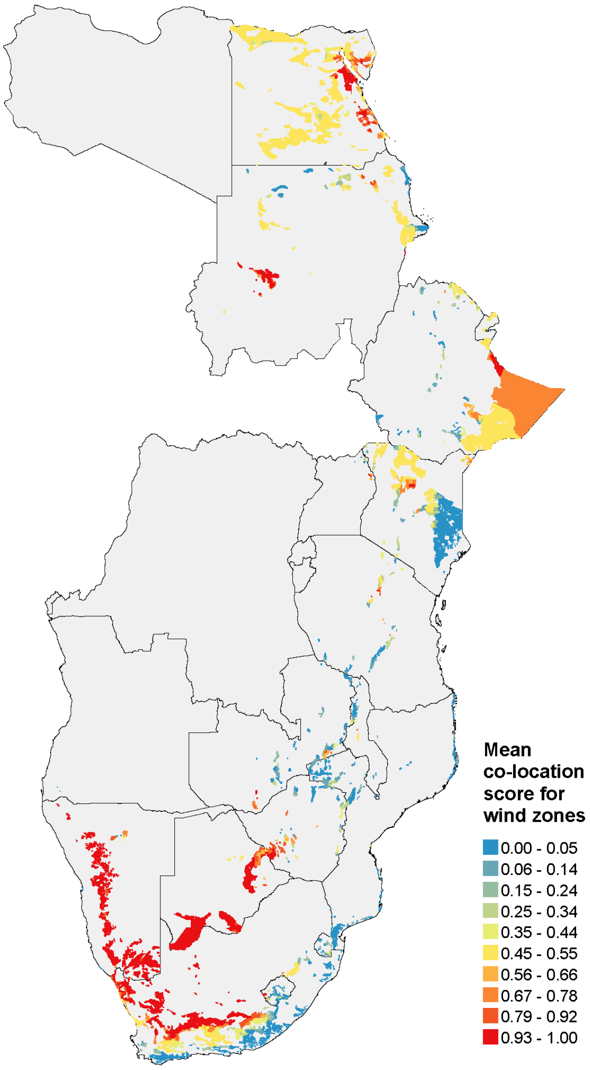


FIGURE 32: Co-location score for wind zones.

The co-location score measures the suitability of an area of land for the development of more than one generation technology. The closer the score is to 0.5, the more project opportunity areas within the zone are suitable for both wind and solar PV. The closer the score is to 1, the more a zone is suitable for wind, solar PV, and solar CSP.

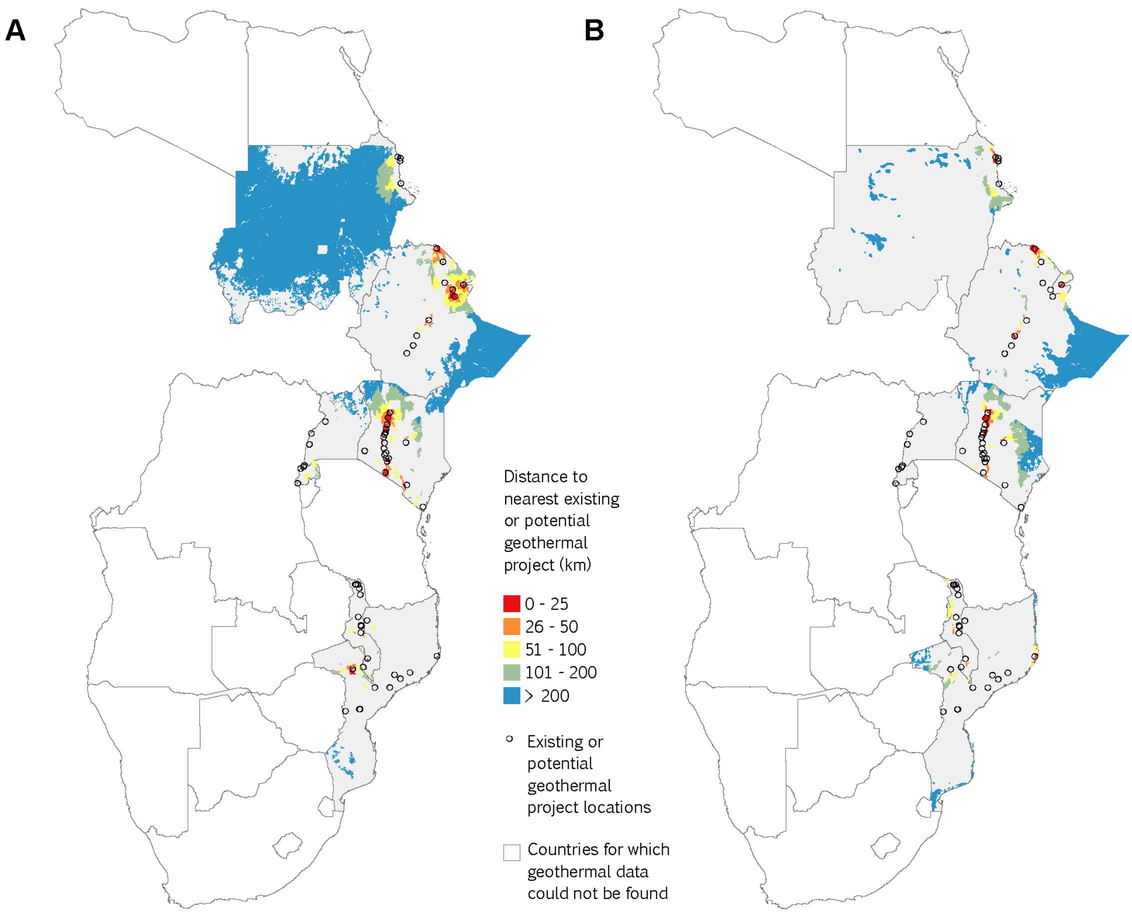


FIGURE 33: Distance to nearest existing or potential geothermal project for each solar PV (A) and wind (B) zone.

Circles indicate the locations of existing or potential geothermal projects.

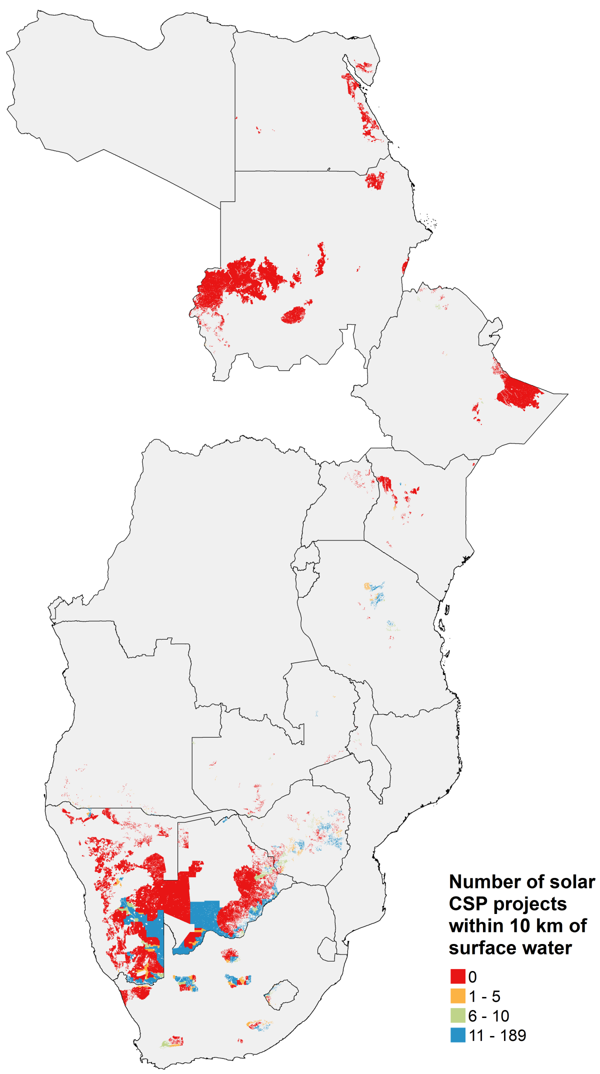


FIGURE 34: Number of project opportunity areas within 10 km of surface water for CSP zones.

Due to its large solar CSP potential, South Africa's analysis is restricted to the renewable energy zones already identified by the South African Strategic Environmental Assessment for wind and solar projects [DEA and CSIR, 2014].

3.3 IDENTIFICATION OF RENEWABLE ENERGY ZONES ACROSS AFRICA CLEAN ENERGY CORRIDOR

Stakeholders may access all zone attributes for each country using the interactive PDF map, which shows location of each zone with respect to other infrastructure and other technologies' zones. Figure 35 - Figure 37 show example images of zones displayed in the interactive PDF for wind, solar PV, and solar CSP zones in Kenya. Interactive PDF maps are available for 20 countries in the ACEC and for the two power pools to support regional planning of renewable energy development.

3.4 SENSITIVITY ANALYSES

We conducted sensitivity analysis on the key parameters of the total levelized cost of electricity (LCOE) for wind, solar PV and solar CSP with 6 hours storage (Figure 38 - Figure 40). We estimated the effect on total LCOE by varying each parameter across a reasonable range of values while holding the other parameters constant at the base case value.

For all three technologies, LCOE is most sensitive to the capital cost, capacity factor, and discount rate (Figure 38 - Figure 40). While we considered a relatively small range of values for wind power's capital cost (estimates for IEC Class I, II and III turbines), we assumed a wider range for capital costs of solar PV and CSP given their uncertainty, rapid cost decline (solar PV), and variation in technology (e.g. parabolic trough versus heliostat tower technologies for solar CSP). The length of interconnection and distance to nearest road individually constitute approximately 5-10% of the LCOE for wind and solar PV and even smaller shares for solar CSP. Discount rate, which is a reflection of the cost of capital, influences the LCOE significantly for all three technologies. While LCOE is an important parameter that estimates the cost of electricity generation, the capacity value may significantly contribute to the value that a site may provide to the overall electricity system. A site with higher capacity value will result in greater cost savings by avoiding investments in conventional generation capacity compared to a site with a lower capacity value. These savings are not captured in the LCOE metric.

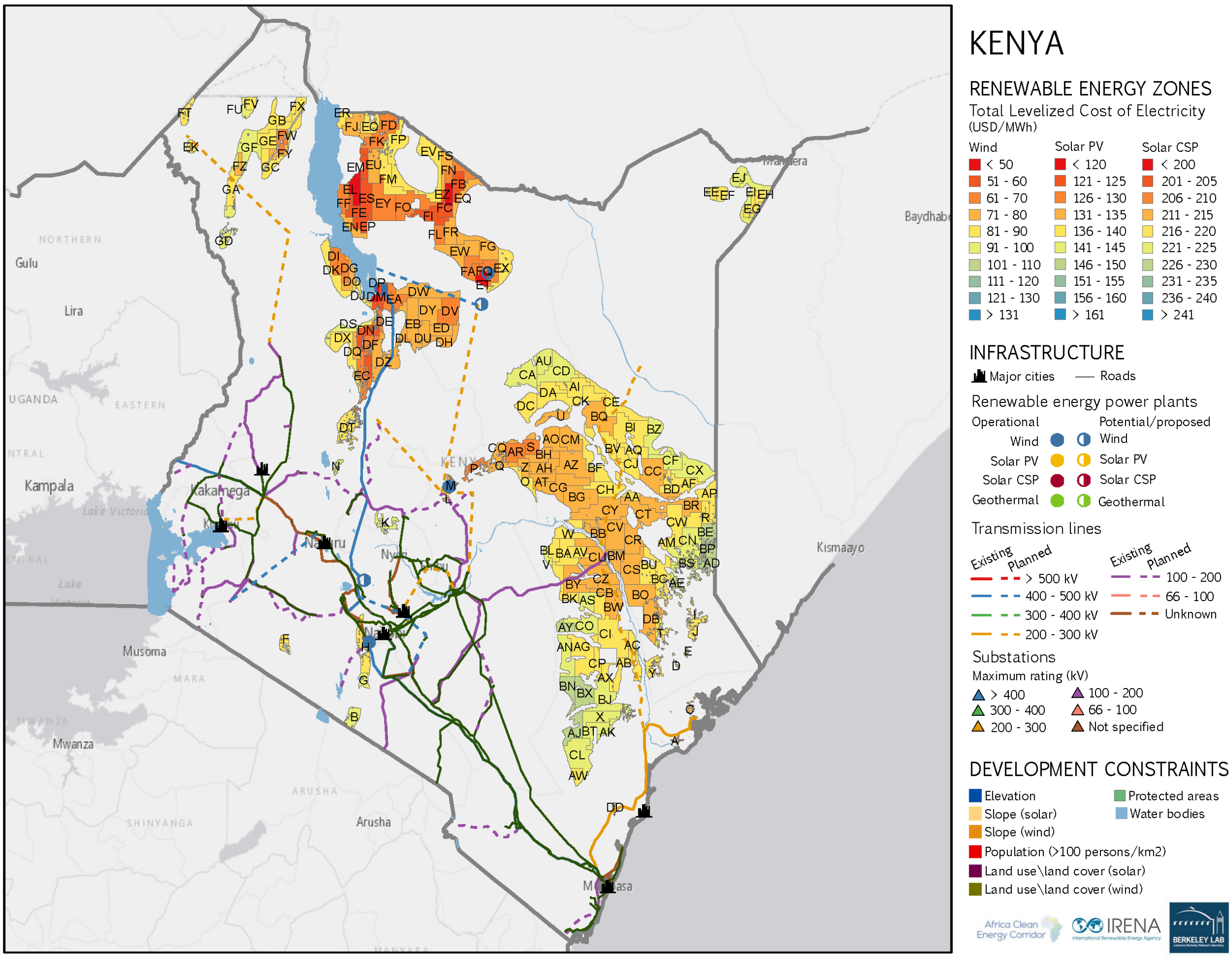


FIGURE 35: Kenya wind zones as shown in the interactive PDF map.

Zones are labeled using unique zone identification letters that correspond to zones in the multi-criteria scoring zone-ranking tool.

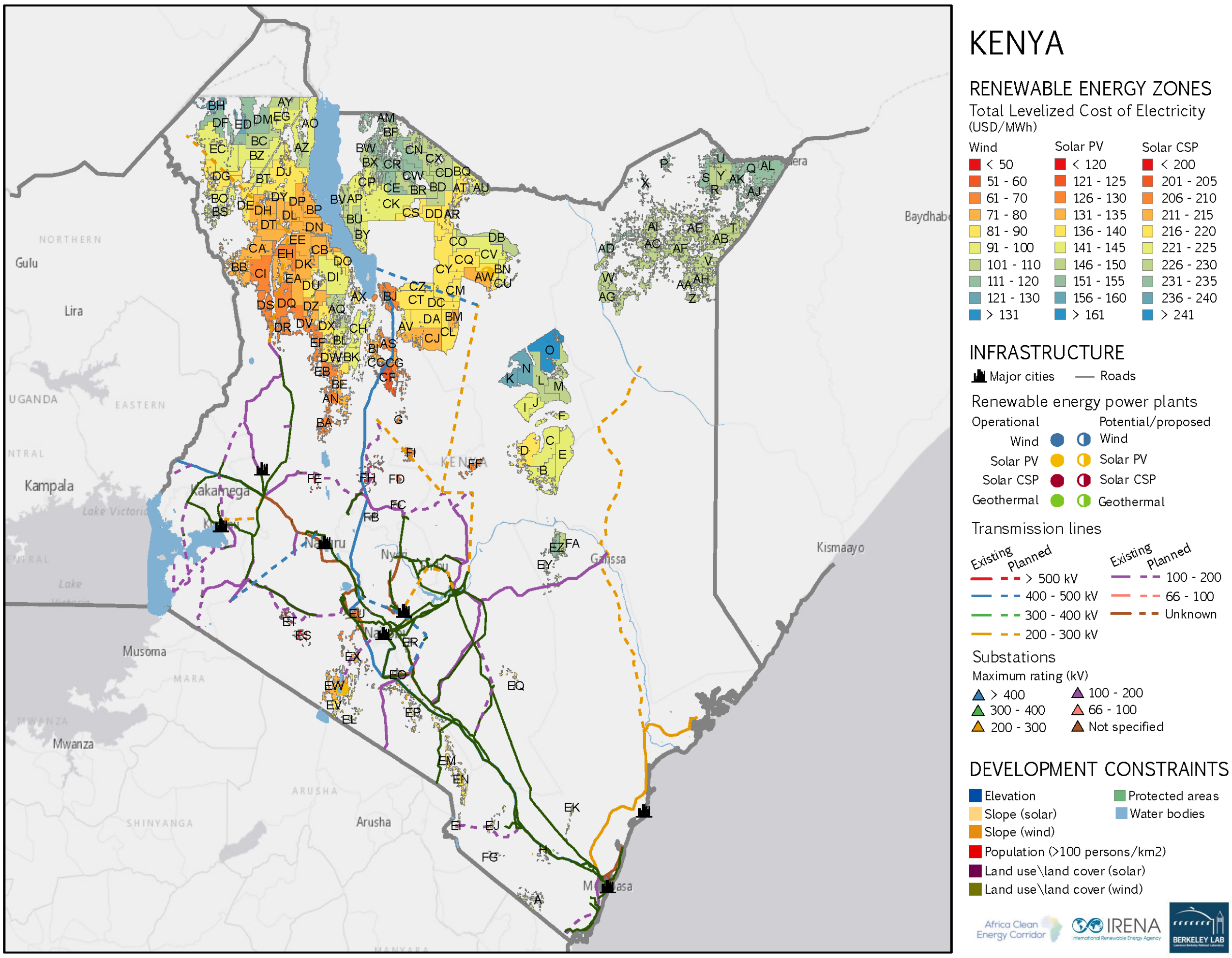


FIGURE 36: Kenya solar PV zones as shown in the interactive PDF map.

Zones are labeled using unique zone identification letters that correspond to zones in the multi-criteria scoring zone-ranking tool.

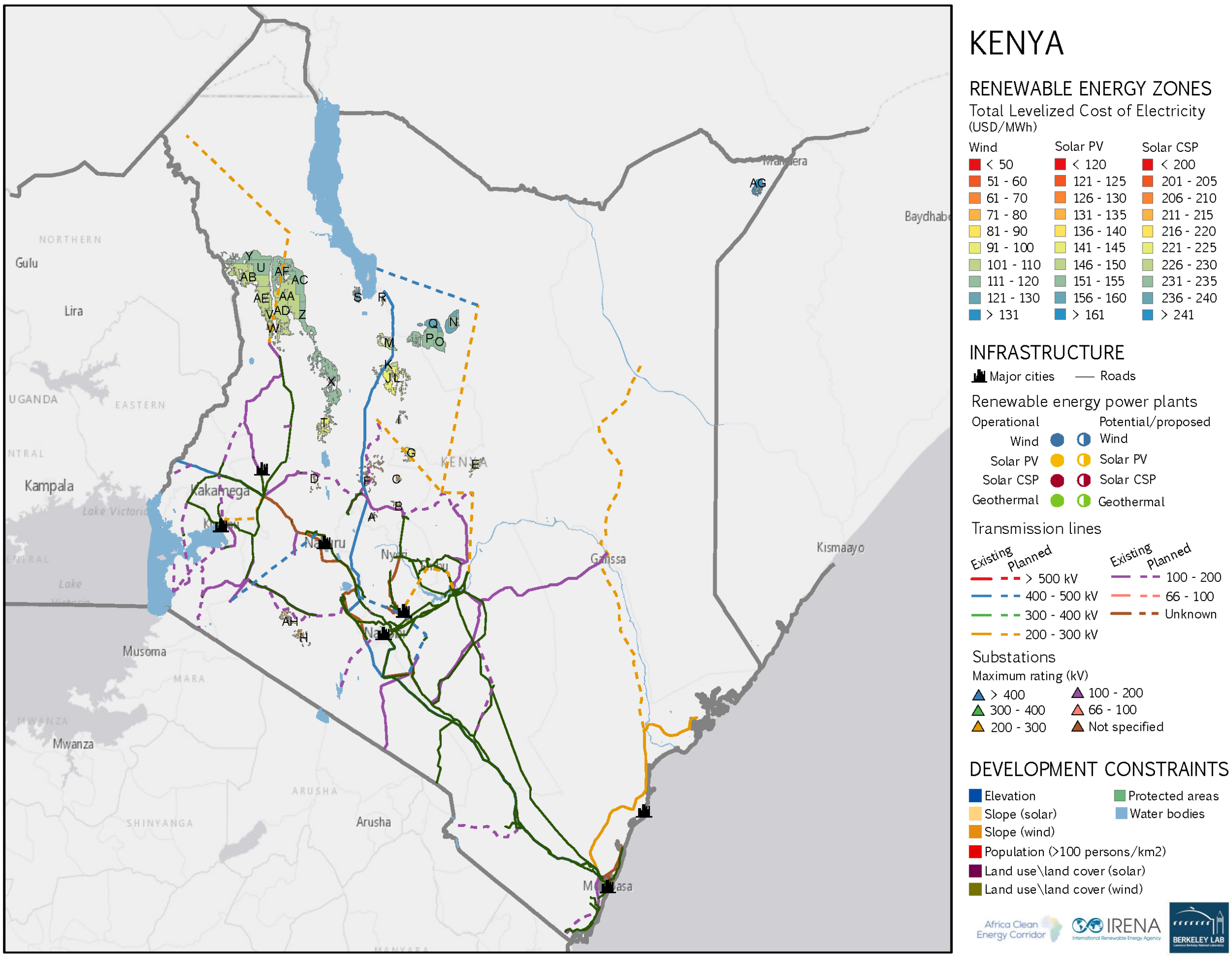


FIGURE 37: Kenya solar CSP zones as shown in the interactive PDF map.

Zones are labeled using unique zone identification letters that correspond to zones in the multi-criteria scoring zone-ranking tool.

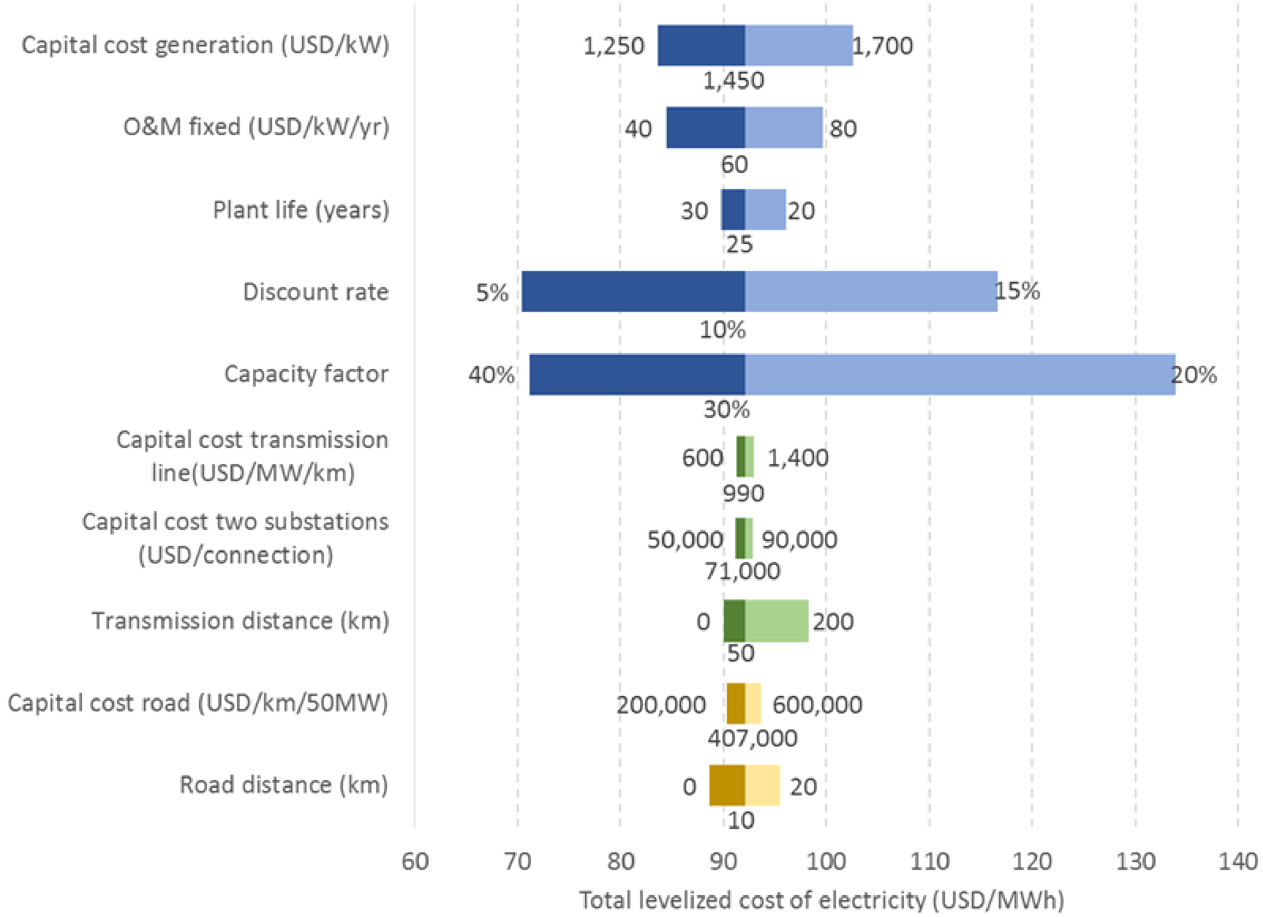


FIGURE 38: Total levelized cost of electricity (LCOE) sensitivity analysis for wind.

The horizontal bars show how the total LCOE varies with different values of input parameters. Numbers under the bar represent the values used in the analysis.

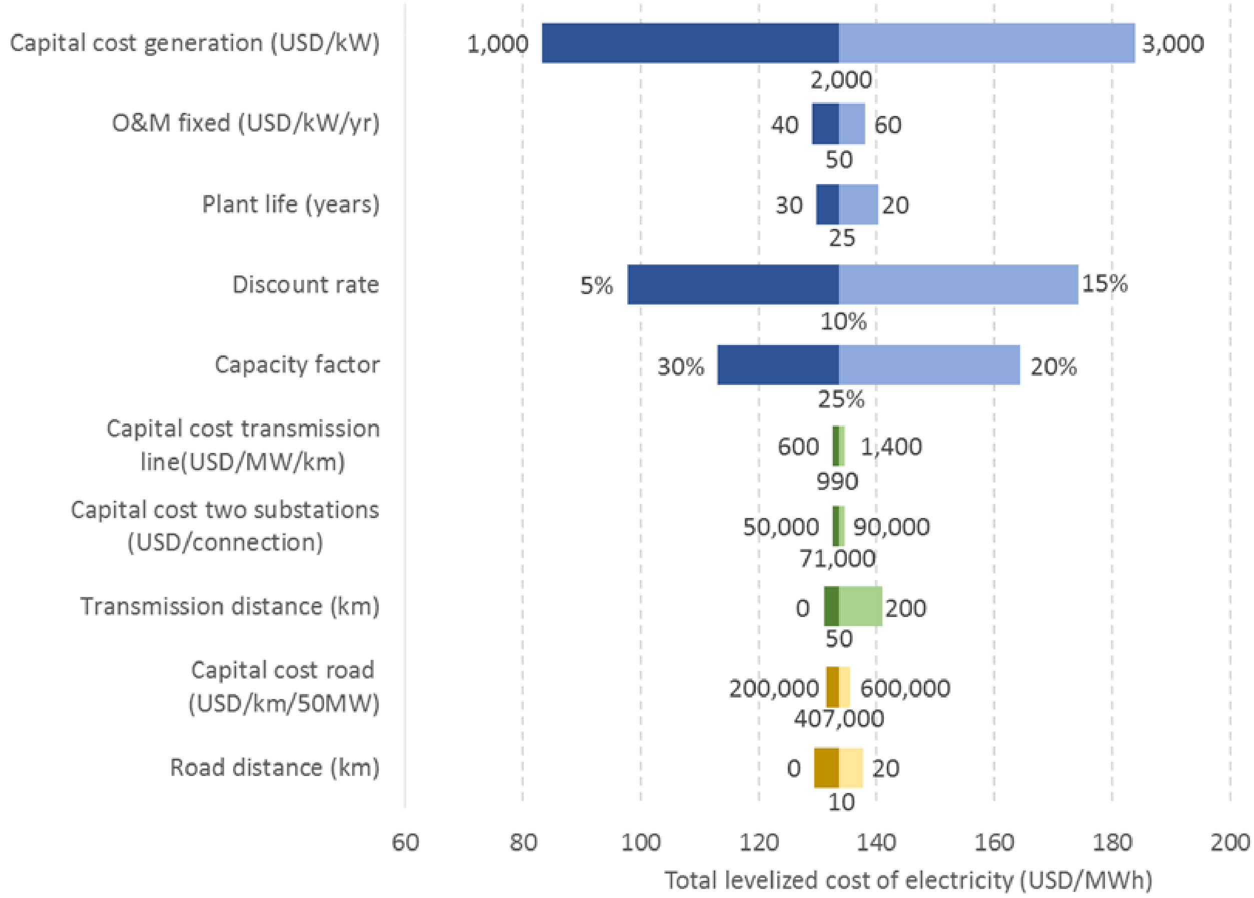


FIGURE 39: Total levelized cost of electricity (LCOE) sensitivity analysis for Solar PV.

The horizontal bars show how the total LCOE varies with different values of input parameters. Numbers under the bar represent the values used in the analysis.

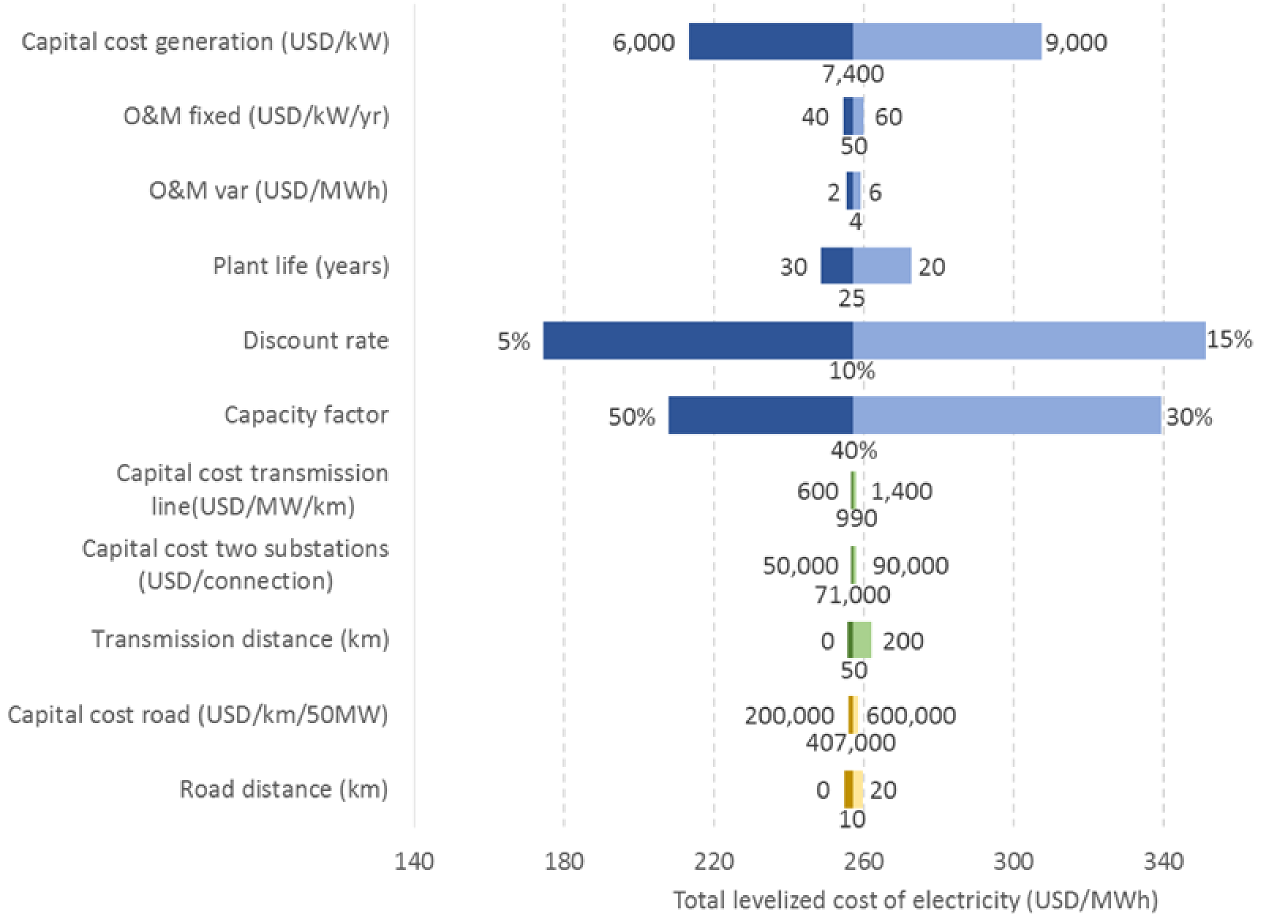


FIGURE 40: Total levelized cost of electricity (LCOE) sensitivity analysis for Solar CSP.

The horizontal bars show how the total LCOE varies with different values of input parameters.

3.5 LIMITATIONS OF THE METHODOLOGY

Results and data derived from meso-scale models such as 3Tier's can be inconsistent with ground-based measurements, as well as data from other meso-scale models such as AWS Truepower or RISOEs simply due to differences in the numerical model or simulation. The type of analysis applied in this study is a first-cut analysis to broadly identify opportunity areas for wind and solar project development. Appropriate long term ground-level data measurements are essential before embarking on project development.

Our study identified large opportunity areas that can be developed as zones and can be connected to the high voltage transmission network for transmitting renewable energy across countries, and potentially across the ACEC region. Smaller areas with high wind or solar potential that may be suitable for development were not considered in our study.

No physical site reconnaissance has been done to verify the results of this study. These analyses better enable and facilitate detailed feasibility studies by robustly identifying the most suitable sites.

We did not have the spatial information to include conflict areas or to examine land ownership constraints. These and other "on-the-ground" information that we were not able to capture in our spatial analysis will be essential to identify the best "bankable" renewable energy zones.

The LCOE estimates in this study, which are based on several assumptions, were primarily provided for comparison between different zones within the study region, and not as absolute cost estimates that can be adopted into policies. The actual costs for a project will depend on several factors including, but not limited to, discount rate (or cost of capital), capital costs of the technology available to the developer, ongoing costs, and actual capacity factors.

Finally, although access to electricity services remains one of the fundamental challenges in Africa, our analysis does not ensure energy access. We identify areas for large utility-scale renewable energy projects, which will enable the increase in clean and sustainable grid-based electricity. However, transmission access, last-mile connectivity, and decentralized energy generation will be needed to expeditiously improve energy access.

4 CONCLUSIONS

Although abundant wind, solar PV, and solar CSP resources exist within the EAPP and SAPP, the uneven geographic distribution of high-quality resources demonstrates that regional collaboration and grid interconnection will be necessary to promote the supply of low-cost clean wind and solar energy to all countries. Angola, DRC, Rwanda, and Burundi lack cost-effective wind zones, but they can benefit from the high-quality wind resources in their neighbouring countries, Tanzania, Zambia, and Namibia. In the case of solar PV, it may be more cost-effective for countries such as Rwanda and Swaziland with lower quality PV potential to import solar PV electricity from Tanzania and South Africa, respectively. **Regional grid interconnection will enable countries to share other renewable resources such as geothermal, as well as conventional resources such as hydro, for balancing the variability of wind and solar generation.** With increasing wind and solar electricity, existing hydro generation in countries such as Ethiopia, Mozambique, DRC, Uganda, Zambia and Malawi could provide balancing services to regional grids. At the same time, solar and wind generation may reduce the risk of interannual and climate-driven variation of hydropower resource availability.

Agricultural land will be important for wind development in particular countries where dual land use strategies could help to spur wind development while supporting farmers economically. Agricultural land comprises about half the wind resource area in Malawi, Mozambique, Tanzania, and Zimbabwe, and greater than half in Zambia. In anticipation of possible land use conflict, policy makers in these countries should pursue land use policies such as land leasing to ensure equitable development that balances multiple uses.

Consideration of wind capacity values using annual peak demand hours substantially increases the geographic distribution and abundance of favorable wind zones, compared to a case that considers only annual average capacity factors. It is crucial to incorporate capacity value, which is a measure for how well generation temporally matches peak demand, in prioritizing wind zones because variable renewable zones with higher capacity values (capacity factors estimated during the peak demand hours within a year) will result in larger offsets in conventional generation capacity. In the ACEC region, many zones with low annual average capacity factors (<30% CF) show capacity values that are comparable and competitive with the high annual average capacity factor zones (>40% CF). Importantly, consideration of wind capacity values increases the number of favorable zones across the ACEC. Moreover, most of the wind zones in countries such as Zambia, Zimbabwe, Mozambique and Tanzania that have lower wind potential, have high capacity value. Finally, many of these high capacity value wind zones are closer in proximity to load centers than zones with high annual average capacity factors.

Almost all countries with sufficient renewable energy potential can develop zones that are cost-effective and have low environmental impact. Many of these zones are also close to existing transmission infrastructure and major load centers, thus requiring lower transmission extension and upgrade costs and lower transmission-associated land use. However, because high-quality, abundant resources also exist in areas that are relatively ecologically intact, development of these zones must be actively avoided through pre-emptive land use and electricity policies that promote low impact development. Additionally, the consideration of capacity value of wind zones as well as LCOE increases the overall suitability of zones that are close to transmission infrastructure, load centers, and have lower environmental impact.

Many wind zones throughout the corridor are also suitable for the development of solar PV, which suggests that co-location could be an important siting strategy to maximize transmission capacity utility, minimize land use, and increase return on investment. In zones suitable for both wind and solar PV development, the space between turbines on a wind farm could be filled with solar PV arrays, with only 1-2% generation loss due to turbine shading. Land and other ancillary infrastructure project costs can be shared between the two generation technologies, which reduces the overall project cost and development risk, particularly for zones further from existing transmission infrastructure.

Renewable energy planning using a multi-criteria approach promotes more socially and environmentally equitable, cost-effective, and reliable generation development. The ACEC renewable energy zones study is the first to conduct detailed multi-criteria wind and solar zoning analysis for the Southern and Eastern Africa Power Pools. The results of this study demonstrate that the best zones for development significantly differ depending on the criteria considered. Stakeholders can use the renewable energy zones interactive map and zone ranking tools, which integrate the results of this study, to determine whether zones have complementary or conflicting siting criteria and to select zones that best resolve conflicts. The feedback and expressed input of stakeholders in multiple stages throughout the process of this study explicitly guided the development of the tool for immediate implementation throughout the region.

Modeling and analysis can only be expeditiously and accurately conducted if government agencies and utilities collect, maintain, and share data. Due to the size of the study region and the integration of multiple project development criteria, this study required an enormous data collection undertaking. We found that the spatial and non-spatial data required to conduct zoning analysis were often not readily available or maintained in digital formats, such as PDFs, ill-suited for spatial or statistical analysis. Although this study was able to identify wind and solar zones using limited data, this and any future study would benefit from more spatial data, such as that on land ownership, conflict regions, nomadic peoples' land use, ecological value, and wildlife corridors. If countries desire to conduct and use zoning studies in the future to inform the rapid development of wind and solar projects that are cost-effective and, socially and environmentally responsible, they will need to actively collect and maintain data to support such studies.

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A DATA AVAILABILITY AND SOURCES BY COUNTRY

TABLE 11: Data availability and sources for Angola, Botswana, Burundi, Djibouti, DRC, and Egypt

Data category	Angola	Botswana	Burundi	Djibouti	DRC	Egypt
Land Use Land Cover (LULC)	Default	Default	Default	Default	Default	Default
Slope and elevation	Default	Default	Default	Default	Default	Default
Protected Areas	a) WDPA b) Protected Planet	a) WDPA b) Protected Planet	a) WDPA b) Protected Planet	a) WDPA b) Protected Planet	a) WDPA b) Protected Planet	a) WDPA b) Protected Planet
Water bodies	Default	Default	Default	Default	Default	Default
Rail	Default	Default	Default	Default	Default	Default
Roads	Default	Default	Default	Default	Default	Default
Substations	Not available	Botswana Power Corporation	Not available	Not available	Not available	Not available
Transmission lines	AICD above 66 kV	AICD above 132 kV	AICD above 30 kV	Not available	AICD above 132 kV	CBI above 132 kV
Existing and proposed geothermal plant locations	None	None	None	Yes	None	None
Existing and proposed wind and solar plant locations	PV and wind - CBI and various sources	PV and CSP – Botswana Power Corporation	None	Wind - CBI	None	Wind, PV, CSP – CBI and various sources
Annual Hourly Demand	Not available	Botswana Power Corporation	Not available	Not available	Not available	Not available
Load centers	Default	Default	Default	Default	Default	Default

Refer to Table 1 for details on "default" datasets.

TABLE 12: Data availability and sources for Ethiopia, Kenya, Lesotho, Libya, Malawi, Mozambique

Data category	Ethiopia	Kenya	Lesotho	Libya	Malawi	Mozambique
Land Use Land Cover (LULC)	Default	Default	Default	Default	Default	Default
Slope and elevation	Default	Default	Default	Default	Default	Default
Protected Areas	a) WDPA b) Protected Planet	a) WDPA b) Protected Planet c) Ministry of Energy	a) WDPA b) Protected Planet c) Lesotho Electricity Company	a) WDPA b) Protected Planet	a) WDPA b) Protected Planet c) MASDAP (Malawi Spatial Data Portal)	a) WDPA
Water bodies	Default	Default	Default	Default	a) Default b) MASDAP (Malawi Spatial Data Portal)	Default
Rail	Default	Default	Default	Default	Default	Default
Roads	Default	SWERA	Lesotho Electricity Company	Default	Default	Default
Substations	Not available	KETRACO	Not available	Not available	Not available	EDM 110 kV above
Transmission lines	AICD 66 kV above	KETRACO	AICD 66 kV above	Not available	ESCOM 132 kV above	AICD 110 kV above
Existing and proposed geothermal plant locations	CBI, web sources	KETRACO	None	Not available	[Dulanya, 2006]	[Martinelli et al., 1995]
Existing and proposed wind and solar plant locations	CBI, web sources	Wind – KETRACO, CBI, various sources Solar PV – [UNEP, 2010] , [African Review, 2012]	Wind - [van der Leek, 2012] Solar PV – [SSI, 2009]	Not available	Wind – [REEEP, 2013]	Wind – [World Bank, 2012] Solar PV - [Ali-Oettinger, 2010]
Annual Hourly Demand	EEPCO	KETRACO	Not available	Not available	ESCOM	EDM
Load centers	Default	Default	Default	Default	Default	Default

Refer to Table 1 for details on "default" datasets.

TABLE 13: Data availability and sources for Namibia, Rwanda, South Africa, Sudan, Swaziland

Data category	Namibia	Rwanda	South Africa	Sudan	Swaziland
Land Use Land Cover (LULC)	Default	Default	Default	Default	Default
Slope and elevation	Default	Default	Default	Default	Default
Protected Areas	a) WDPA b) Protected Planet c) Ministry of Environment and Tourism, Government of Namibia	a) WDPA b) Protected Planet	a) WDPA b) Protected Planet c) DEA	a) WDPA b) Protected Planet	a) WDPA b) Protected Planet c) Swaziland Electricity Company (SEC)
Water bodies	Default	Default	Default	Default	Default
Rail	Default	Default	Default	Default	Default
Roads	Default	Default	Default	Default	Default
Substations	NamPower	REDCL 70kV above	a) Eskom 220 kV above b) TDP 2015 Eskom 220 kV above	Not available	Swaziland Electricity Company (SEC)
Transmission lines	NamPower; 66 kV above	REDCL 70kV above	a) Eskom 220 kV above b) TDP 2015 Eskom 220 kV above	CBI 132 kV above	Swaziland Electricity Company (SEC); 132 kV above
Existing and proposed geothermal plant locations	None	CBI	None	[Evans and Tammemagi, 1974]	None
Existing and proposed wind and solar plant locations	Wind – CBI, web sources Solar CSP - [Renewable Energy and Energy Efficiency Institute (REEEI) and GESTO Energy Consulting, 2012]	Wind, solar PV – CBI and various sources	Wind - Eskom Solar PV – Eskom Solar CSP - Eskom	Wind - [RECREE, 2012] Solar PV - [RECREE, 2012]	Wind – CBI and various sources
Annual Hourly Demand	NamPower	Not available	Eskom	Ministry of Water Resources and Electricity	Swaziland Electricity Company (SEC)
Load centers	Default	Default	Eskom	Default	Default

Refer to Table 1 for details on "default" datasets.

TABLE 14: Data availability and sources for Tanzania, Uganda, Zambia, Zimbabwe

Data category	Tanzania	Uganda	Zambia	Zimbabwe
Land Use Land Cover (LULC)	Default	Default	Default	Default
Slope and elevation	Default	Default	Default	Default
Protected Areas	a) WDPA	a) WDPA	a) WDPA	a) WDPA
		b) Protected Planet c) UNEP GeoIQ	b) Protected Planet c) Government of Zambia	b) Protected Planet
Water bodies	Default	Default	Default	Default
Rail	Default	Default	Default	Default
Roads	Default	Default	Default	Default
Substations	Not available	Not available	ZESCO 66 kV above	Not available
Transmission lines	Geocoded TANESCO transmission tower locations; 132 kV above	UETCL	AICD 66 kV above	AICD 66 kV above
Existing and proposed geothermal plant locations	None	UNEP GeoIQ	None	None
Existing and proposed wind and solar plant locations	Wind – TANESCO Solar PV - TANESCO	Solar PV - CBI	Solar PV – Energy Regulation Board of Zambia	Wind and solar PV – CBI and various sources
Annual Hourly Demand	TANESCO	Government of Uganda	ZESCO	ZERA
Load centers	a) Default b) TANESCO	Default	Default	Default

Refer to Table 1 for details on "default" datasets.

B AFRICA CLEAN ENERGY CORRIDOR: MAPS OF RESOURCE CONSTRAINTS AND OTHER CRITERIA

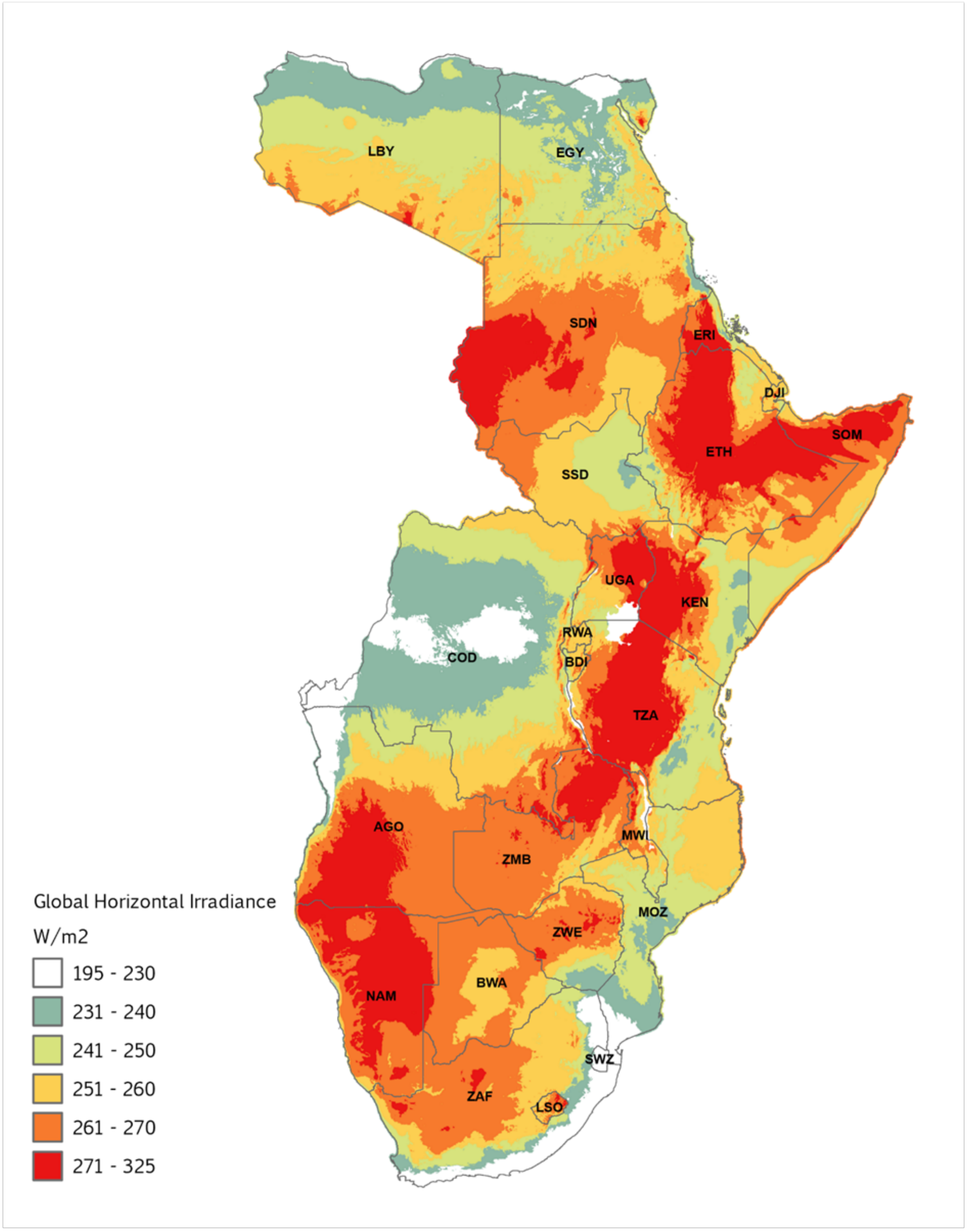

FIGURE 41: Global Horizontal Irradiance (Solar PV resource) above the minimum resource threshold.

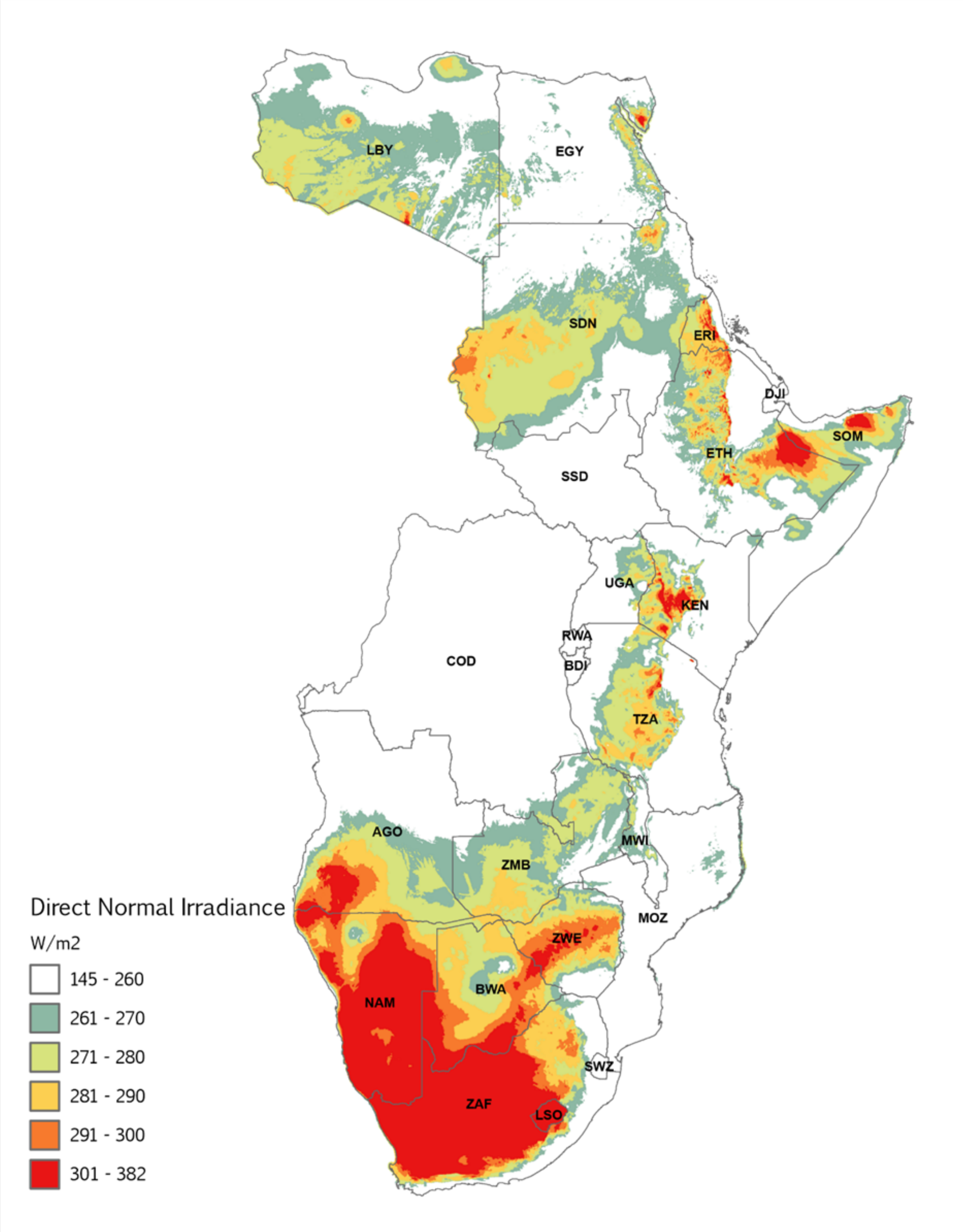

FIGURE 42: Direct Normal Irradiance (solar CSP resource) above the minimum resource quality threshold.

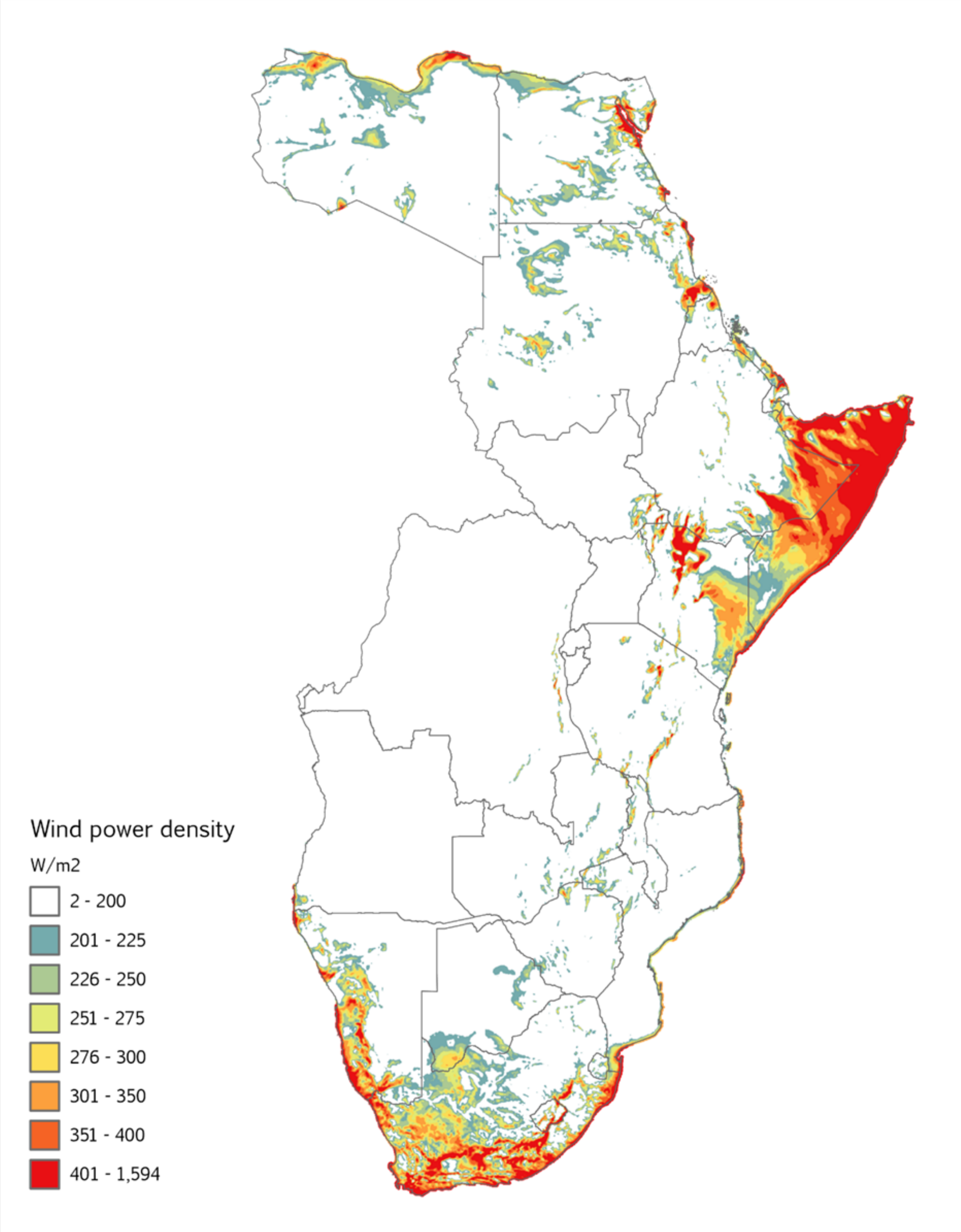

FIGURE 43: Wind power density (wind resource quality) above the minimum resource quality threshold.

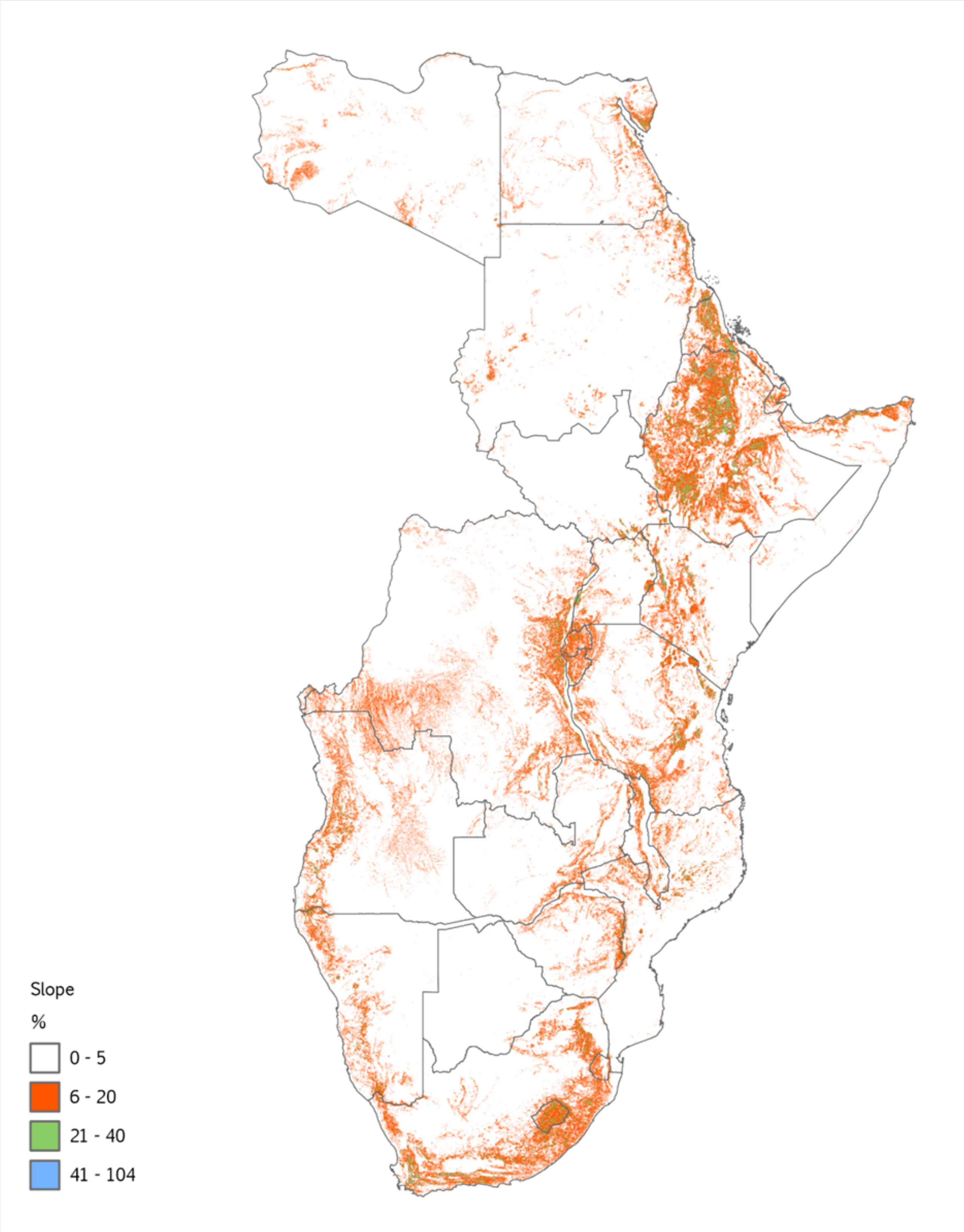

FIGURE 44: Areas with slope above the solar (5%) and wind (20%) thresholds used as maximum values in resource assessment.

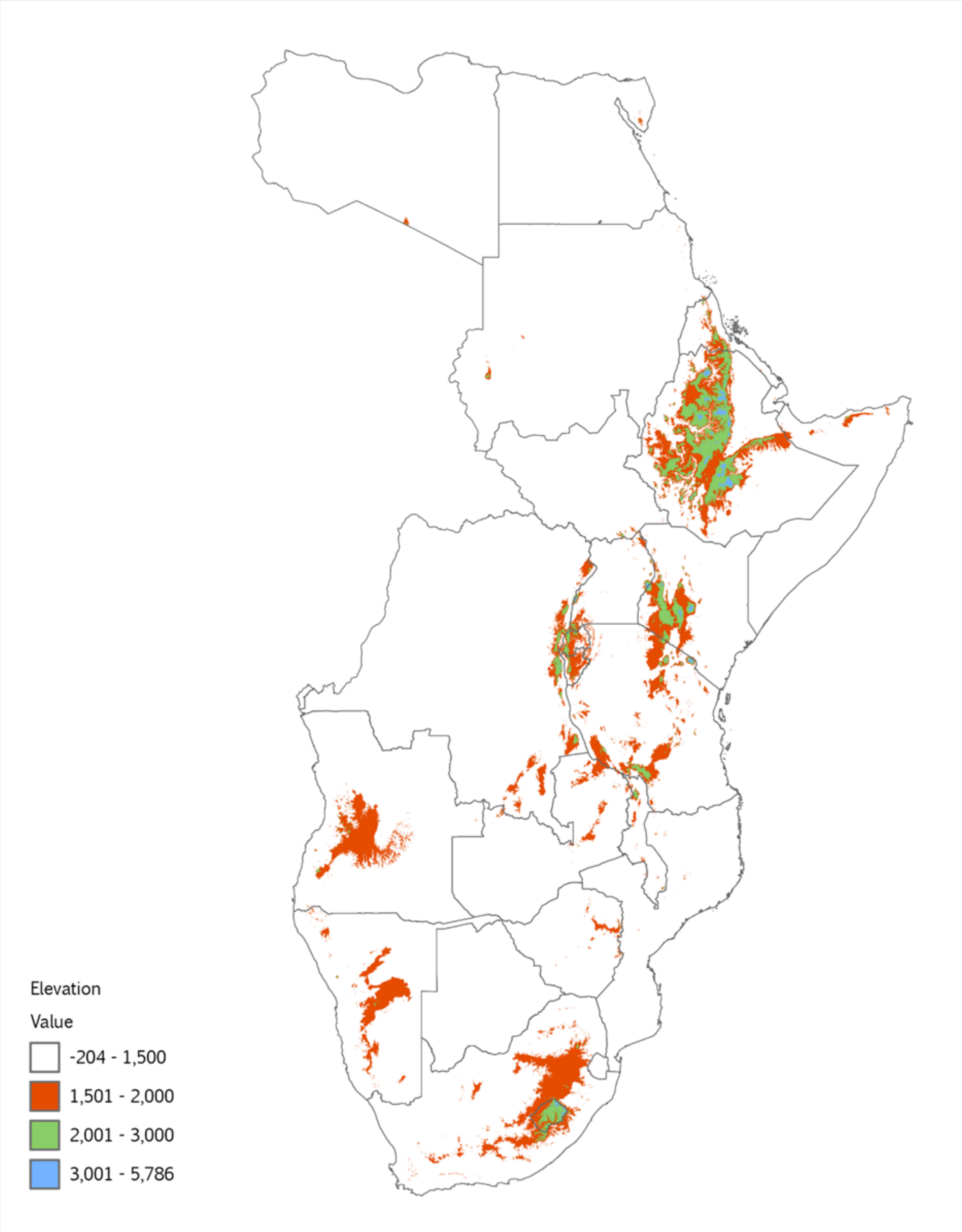

FIGURE 45: Areas with elevation above the resource assessment maximum thresholds (1500 – 3000 m).

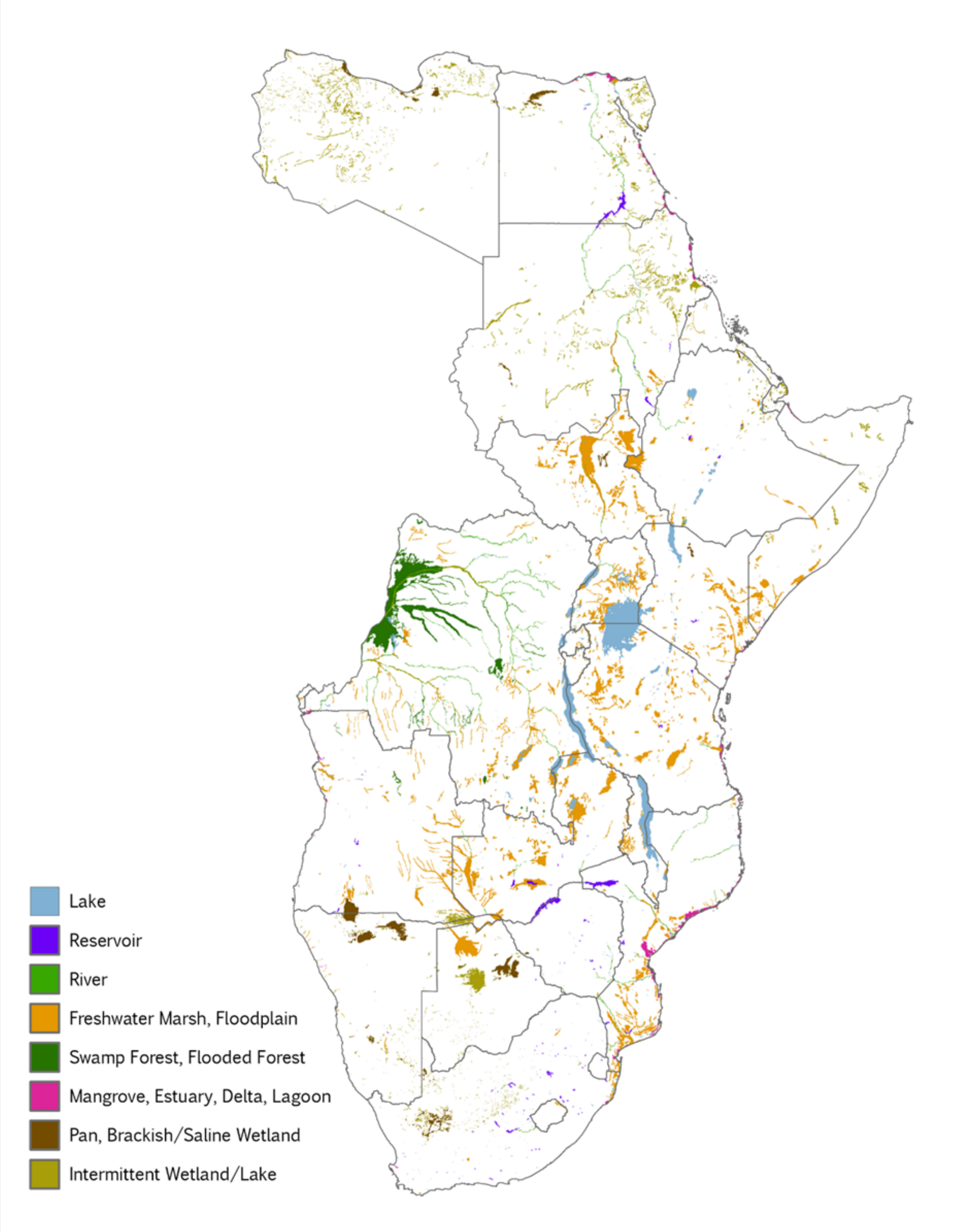

FIGURE 46: Surface water exclusions used in resource assessment.

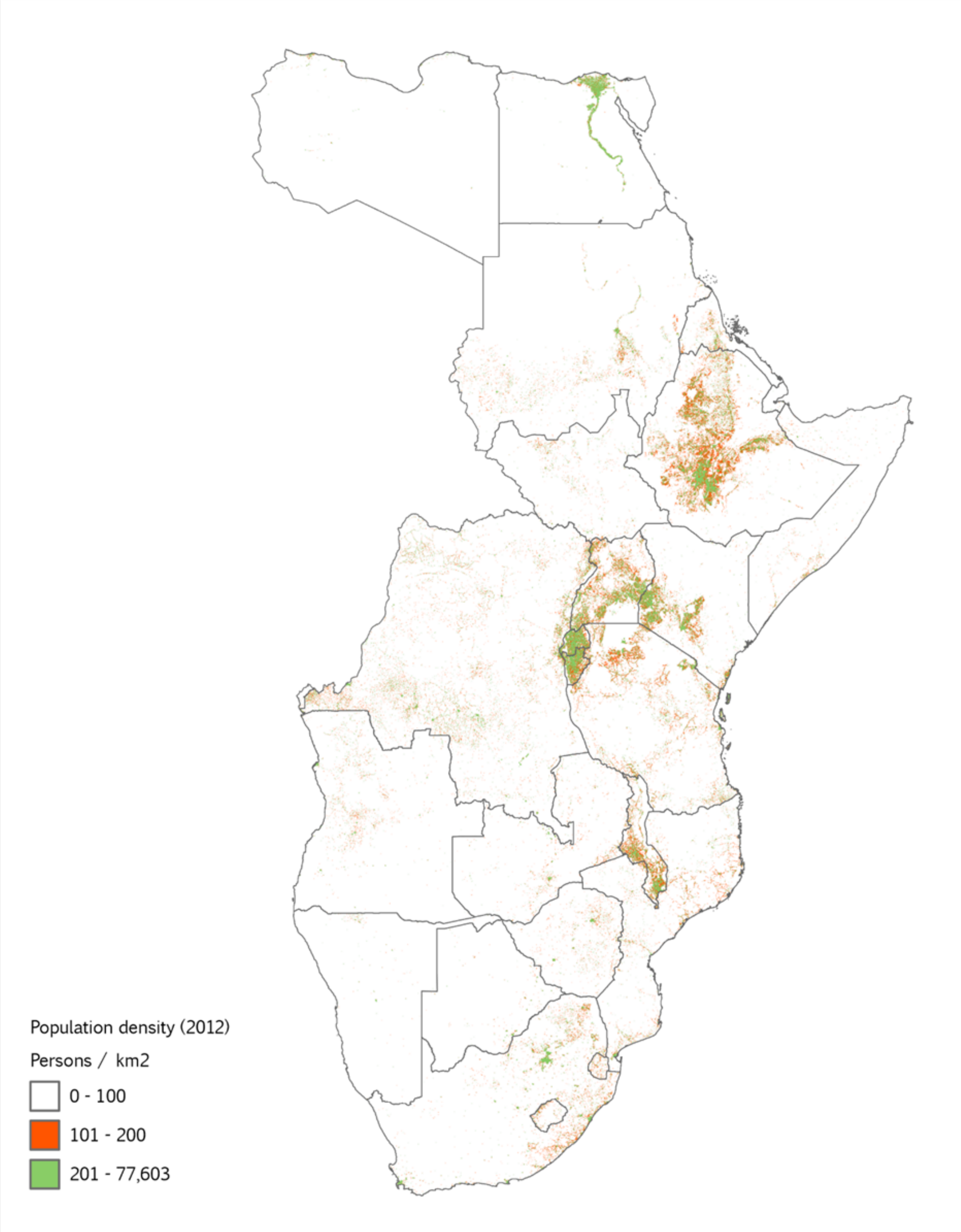

FIGURE 47: Areas with population density above the resource assessment maximum threshold (100 persons/km^2).

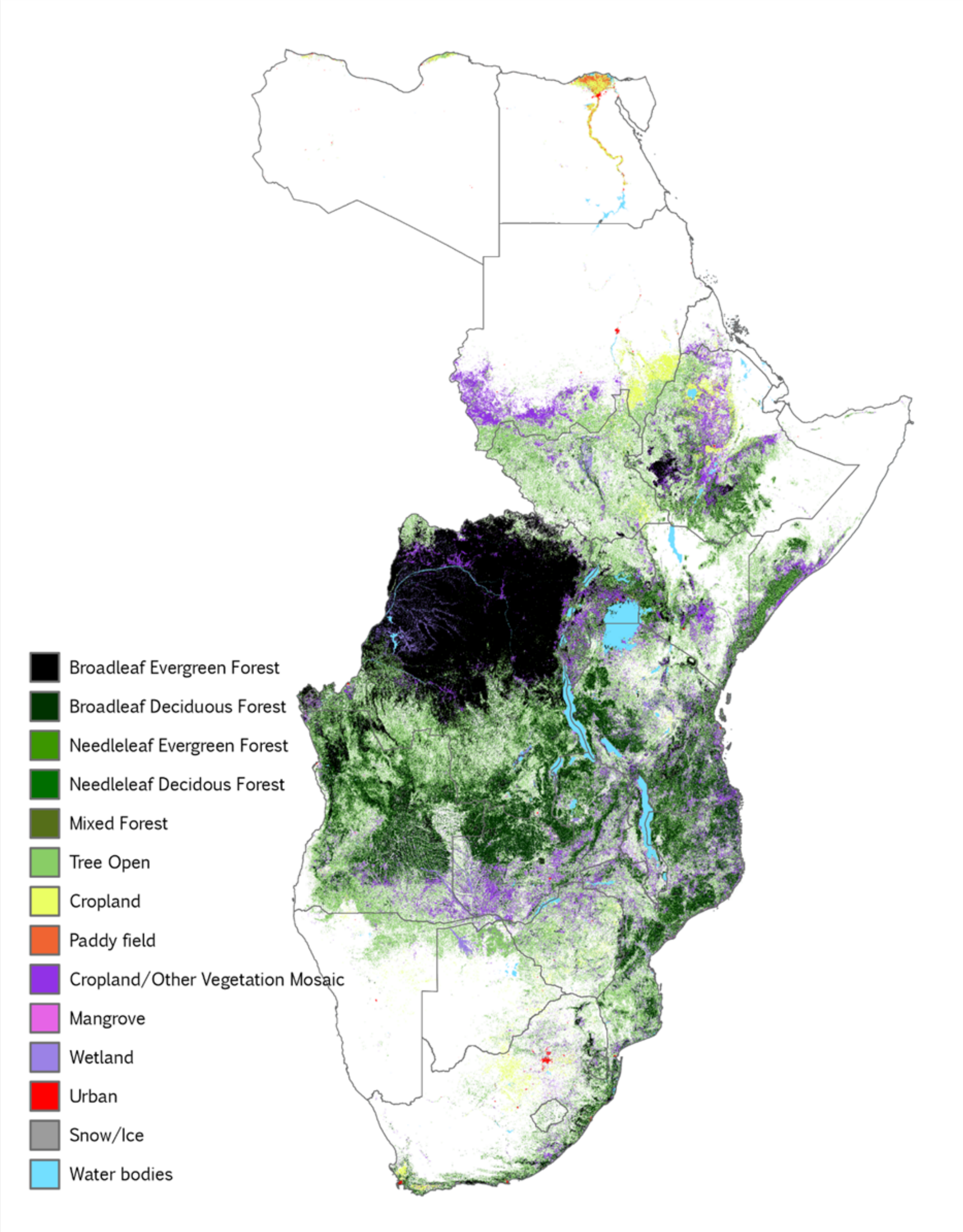

FIGURE 48: Land use and land cover exclusion categories for solar technologies.

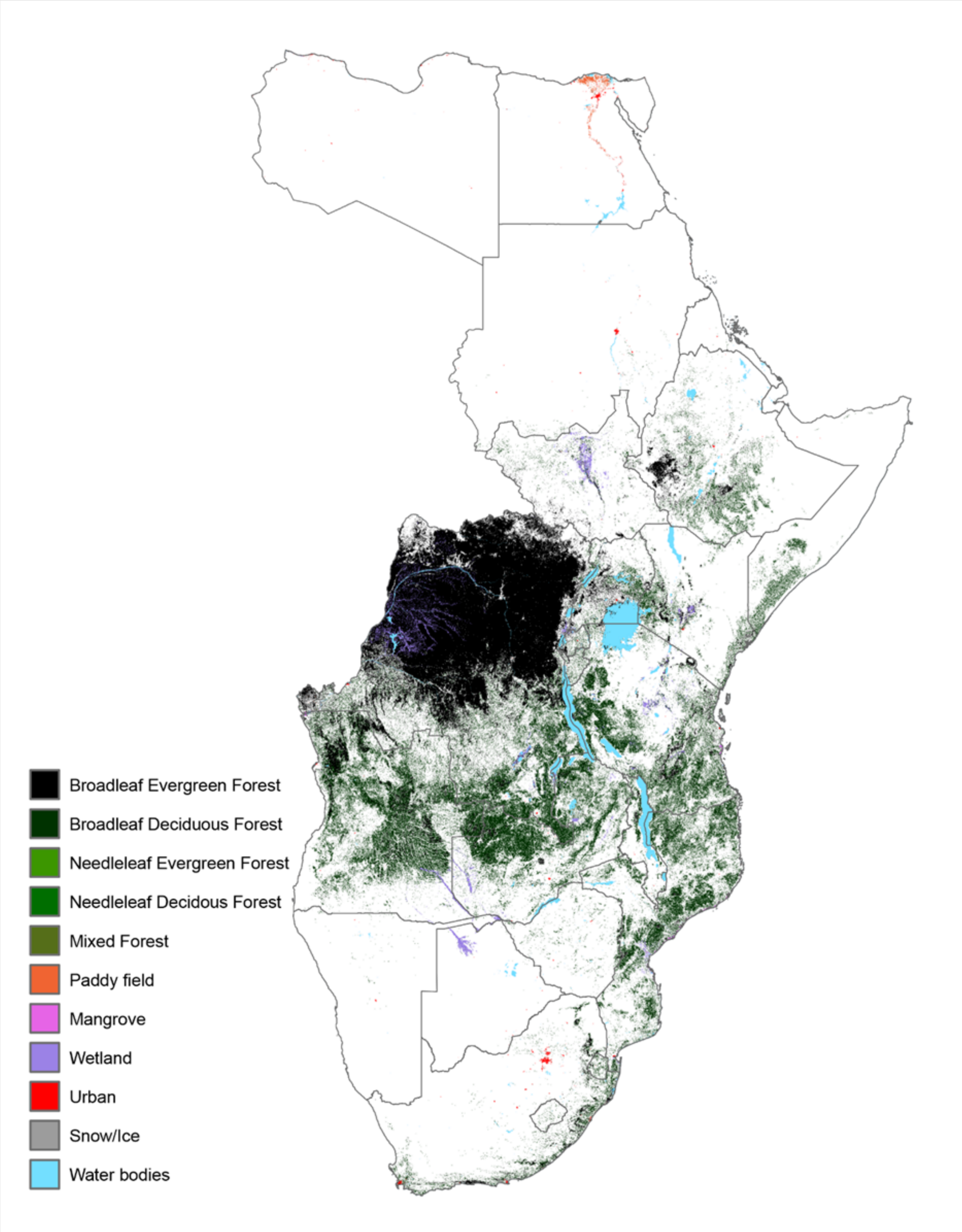

FIGURE 49: Land use and land cover exclusion categories for wind.

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