Europa-Universität Flensburg

DISSERTATION

Spatial disaggregation of grid-connected renewable energy source systems for rural electrification in Ghana

Mary Asare-Addo

Supervisors

Prof. Dr. Bernd Möller

Prof. Dr. Olav Hohmeyer

A thesis submitted in fulfilment of the requirements for the degree of Dr. rer. pol

Interdisziplinäres Institut für Umwelt, Sozial- und Humanwissenschaften
Abteilung Energie- und Umweltmanagement

August 2023

Abstract

This dissertation presents a summary of the resource potential assessments for wind energy, solar energy from solar PV and CSP systems as well as the viability of green hydrogen production in Ghana from wind and solar PV. The main goal of the dissertation is to analyse the possibility of improved sustainable energy access through grid integration. To achieve this purpose, geospatial techniques combined with multi-criteria decision methods were applied to quantify the theoretical, geographical, technical, and economic potentials of the renewable resources at various disaggregated scales across the country. Part of the research also included an evaluation of the electrification policy of Ghana and its implications for the country's energy systems decarbonisation targets. Key findings from the research observed that many of the areas with very good generation capacities do not meet all requirements for a grid-connected system but rather for off-grid solutions. This will in effect slow down the diversification of the energy generation mix as by comparison, grid-electrification has more supply capacity than off-grid solutions like solar home systems and mini-grids.

Keywords: Geospatial; renewable resource mapping; sustainable energy access; multi-criteria decision; Ghana.

Executive summary

The fight against climate change and global warming remains unabated. The impact of climate change both on the society and the environment cannot be overemphasized. Its impacts transcend all geographies, altering the lives of people globally. It is now widely known that climate change is caused by the increasing amount of greenhouse gases in the atmosphere and the continuous impact of human activities exacerbating an already existing climate change challenge can also not be downplayed and are well documented in the literature. Since the 1800s, the activities of human have been the main driver of climate change, primarily due to the burning of fossil fuels like coal, oil, and gas [1]. Also, according to the UN climate action report, the energy, transport, buildings, agriculture and land use are among the main sectors responsible for greenhouse gas emissions [1]. The energy sector alone accounts for about two-thirds of total global greenhouse gas emissions, and thus the energy sector plays a central role towards efforts to reduce these emissions and help mitigate climate change [2].

Following this, in the year 2010, the United Nations General Assembly passed a resolution to mark the year 2012 [3] as the International year of *Sustainable Energy for All* and as a commencement and awareness year in championing the *SE4All* Agenda. The year was set in recognition of the increasing importance of energy as a catalyst for economic development and as a *climate change mitigation strategy* [4]. The initiative was hence tied closely to the 2015 Sustainable Development Goal 7 to ensure that all member countries achieve universal access to clean energy by the year 2030, and also as a clarion call on all member countries to fulfil their commitments to the Paris Agreement that calls for measures to manage global warming to 1.5 degree Celsius by reducing the amount of greenhouse gases in the atmosphere [5]. And thus, with commitment to fulfilling the UN Agenda 2030, which also includes sustainable energy access for all, members countries were advised to put in efforts to incorporate this agenda in their national energy policies and climate change program interventions to meet the sustainable energy for all targets.

Renewable resources have proven to be a very viable mitigation strategy for energy system decarbonisation, as well as a cost competitive source of energy in achieving the sustainable energy for all targets [6]. The present research thus explored the potential of solar and wind resources including the potential to produce green hydrogen using solar PV and wind energy at a more disaggregated level in Ghana through the application of GIS-based multi-criteria approaches. Results of the analysis showed varying potentials across all regions in the country, but a striking observation showed that, many of the high potential areas may not be considered for grid

integration or grid connected electrification because they do not meet the existing grid connection requirement rule per the country's electrification policy as of today. Thus, as a policy recommendation, the research recommends policymakers in Ghana to review the national electrification policy or set priority projects to enhance the development and deployment of energy transition projects in order to meet its Agenda 2030 commitments and targets.

Declaration of interest

The author declares that there are no competing interests.

Acknowledgements

The author would like to thank the Europa-Universität Flensburg for the opportunity to pursue a PhD with the university. Thank you to my academic supervisors, Prof. Dr. Bernd Möller, and Prof. Dr. Olav Hohmeyer for their guidance. I would like to also express my gratitude to my family and friends for their continuous support and encouragement.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

AHP	Analytic Hierarchy Process	LCOE	Levelized Cost of Energy
CI	Consistency Index	NDCs	Nationally Determined Contributions
CR	Consistency Ratio	O&M costs	Operations and Maintenance costs
CSP	Concentrated Solar Power	PEM	Proton Exchange Membrane
DNI	Direct Normal Irradiance	PR	Performance Ratio
GHI	Global Horizontal Index	RI	Random Index
GIS	Geographic Information Systems	SDG 7	Sustainable Development Goal 7
GSA	Global Solar Atlas	SE4All	Sustainable Energy for All
GWA	Global Wind Atlas	Solar PV	Solar Photovoltaics
HHV	Higher Heating Value	UN	United Nations
IPCC	Intergovernmental Panel on Climate Change	WPD	Wind Power Density
IRENA	International Renewable Energy Agency		

Definition of key terms

a. ***Spatial disaggregation*** as used in the context of this research is an areal weighting method by which the known counts of surfaces or spatial features associated to source administrative regions are divided uniformly across the administrative area, in order to generate estimates at regions of higher spatial resolution [7]. It simply refers to the downscaling of data at a coarse scale to a finer scale while retaining consistency with the original dataset. It is a relevant and rapid approach for evaluating and developing high-resolution climate change surfaces for high resolution regional climate change impact and mitigation assessments, with less likelihood of altering the original data patterns [8].

b. The concept ***rural*** does not have a universally accepted definition. The term ***rural*** therefore, as used in the context of this research broadly refers to all remote areas or areas beyond the maximum power grid network threshold to an extent that, it is not economically viable or prudent to supply those areas with on-grid electrification but rather service those areas using off-grid electrification solutions.

1. Introduction

Access to not just energy but *sustainable* energy is a challenge in Ghana. It is also widely acknowledged that the lack of it has rippling negative impacts on various aspects of human life and development such as on health [9], education [10], quality of life, wealth, gender equality [11, 12], poverty, as well as the development of a country. And as such, the level of energy access has become a development indicator used to track the progress of a country. Besides, access to basic energy remains a huge challenge in the Sub-Saharan African region and according to the recent 2023 energy progress report [13], to bridge this gap, people living in rural or remote areas must have an annual access rate of growth of one percent point per year, i.e., almost twice the current pace, else about 660 million people in the region will remain unserved by 2030 [13, 14]. Many people in the region still rely on unconventional energy sources like kerosene for lighting, and fuelwood, farm residue, and charcoal as fuel sources for cooking with its associated health risks [13].

In Ghana, even though the country has made significant progress towards reducing energy poverty, about 14% of the population still lack access to electricity [15]; and with a wide access gab between rural (74%) and the urban (95%) population, and thus about 26% of the rural population still live without access to electricity. The situation is even dire and urgent when it comes to access to clean cooking as out of a population of about 33 million people [15], about 22 million are without access to clean cooking fuels and technologies [15].

Furthermore, even though access to electricity in the country has improved over the past 10 years, with current rate of access at 86%, the country is still far from meeting its decarbonisation targets by 2030. This is because the country's energy mix is predominantly fossil-based —accounting for about 66% [16] of the total energy generation mix, with 32.9% from hydropower and only about 0.7% from renewables (solar PV and biogas)[16]. Thus, diversification of its energy supply system has become even more urgent towards fulfilling the government's commitments towards the Paris Agreement and Agenda 2030, with focus on the SDG 7 targets. The SDG 7, for which Ghana has committed to, seeks to achieve three core targets by 2030, for which all UN member countries, must i) *ensure universal access to affordable, reliable, and modern energy services*; ii) *increase substantially the share of renewable energy in the global energy mix*; and iii) *double the global rate of improvement in energy efficiency* [17]. Renewable resources have proven to be a very viable mitigation strategy for energy system decarbonisation, as well as a cost competitive source of energy [6]. Ghana, due its geographical location, is fortunate to have several renewable resources such as abundant solar, biomass, hydropower, geothermal, and even wind energy and a green hydrogen potential to harness.

However, a major challenge that hinders the exploitation of renewable energy resources is the ability to locate and quantify the exact generation capacity of these resources to determine their viability. As such, according to the country's renewable energy masterplan [18], two of the major challenges hindering the development of renewable energy in the country are the uncertainties associated with the availability of the resources as well as limited technology capacities to harness these resources. This thus forms the basis of this research — which is to help the government of Ghana address these challenges by mapping and quantifying the solar and wind energy potentials, including the green hydrogen potential, at various scales, especially at a more disaggregated regional level through the application of geospatial science.

Several statistical and mathematical methods have been applied in the literature to estimate the potential of renewable energy of a location. However, among these methods, the application of geographic information systems (GIS) has gained increasing preference in recent times. This is because the application of GIS also allows for the integration of multi-criteria decisions such as local land use policies, climatic conditions as well as the energy policies that may impact the development and deployment of the renewable energy project [19–21]. Besides, GIS can help identify spatial problems, address the problems, and present results using high resolution maps, thereby bringing reality to its audience like project stakeholders. These major factors are what distinguishes GIS-based approaches from other methods and applications. Examples of case studies where GIS has been used to estimate renewable resource potentials include [22–35].

1.1. State of Research

This dissertation can be placed in the broad field of climate science and as a climate change mitigation strategy. The research seeks to contribute towards the global call to minimize and limit global warming to 1.5°C [5]. The present research precisely, tries to contribute to the overall SDG 7 targets under the *Sustainable Energy for All* agenda by building on existing energy systems decarbonisation pathways using the renewable resources available within a country. Current science and research have proven that renewable resources are very viable mitigation strategy for energy system decarbonisation, as well as a cost competitive source of energy [6]. And thus, the UN recognises the role and contribution of science and research in meeting the 1.5°C global warming targets [5]. However, even though a review of the literature shows that there exist many and different decarbonisation pathways used to assess the viability of the renewable resource potential in a country, the present research builds on the existing resource potential mapping models through the integration of geospatial science and based on this, designed a GIS-based multi-criteria framework for evaluating the renewable resource potential in a country. Particularly, with the application of GIS for resource potential assessment, the present study does not only address the technical and economic viability of the renewable resources, but also tried to understand and map out how the local climatic conditions of a location can influence the scale of the energy potential of the location. The contribution of this research to science, does not also only end here, as the research also tried to understand and address a major concern which is currently gaining attention and an under-researched area, which is to integrate and estimate the environmental and social dimensions or criteria of a country such as considerations to the energy policy and regulations of a country and their impact on the overall energy transition projects in a country at a more spatially disaggregated level. The use of multi-decision criteria allows for the integration of such social indicators even at an appropriate disaggregated level. The integration of the social component at a spatially disaggregated level is a relevant approach, not only for research but also for policy making, because an efficient policy framework most often requires information or data with high degree of spatial disaggregation [36]. Each of the three scientific articles have been synthesized to highlight how the proposed GIS-based multi-criteria framework used in this study contributes to the current state of research with regards to renewable resources potential assessments and feasibility studies.

Further, the scope of the present research focuses on how the renewable resources such as solar and wind as well as the production of green hydrogen can be harnessed to contribute towards meeting the energy sustainability targets. This research also adopted a bottom-up approach and it is under the assumption that, the decentralization of climate change mitigation measures is one major approach towards achieving a unified sustainability goal by looking at how local communities, given their renewable resources can be harnessed and developed to the benefit of not only the country but also contribute to the overall global call to limit the global average temperature to the 1.5°C target.

The framework used in this research is also thus expected to serve as a model that could be scaled-up and replicated across other African countries or geographies.

1.2. A brief history behind the *Sustainable Energy For All* Agenda 2030

In the year 2010, the United Nations General Assembly passed the resolution 65/151 to mark the year 2012 as the International year of *Sustainable Energy for All* and as a commencement and awareness year to champion the *SEforALL* Agenda [3]. The year was set in recognition of the increasing importance of energy as a catalyst for economic development and as a *climate change mitigation strategy*. It was an agenda to review the role of energy in tackling issues related to development and to rectify the error of not including energy poverty in the Millennium Development Goals. It was then based on recommendations from this report in 2010, that the Sustainable Energy for All initiative was launched in 2011 [4] as a preparatory year to spearhead the International year of Sustainable Energy for All for 2012. The initiative was then tied closely to the 2015 Sustainable Development Goal 7 to ensure that all member countries achieve universal access to clean energy by the year 2030 and also as a clarion call on all member countries to fulfil their commitments to the Paris Agreement that calls for measures to manage global warming to 1.5 degree Celsius by contributing to reducing the amount of greenhouse gases in the atmosphere.

Hence, with commitment to fulfilling Agenda 2030, all the member countries were admonished to develop their Nationally Determined Contributions (NDCs) [37] roadmap in alignments with the *SE4All* targets, particularly with regards to how their national energy policy and regulatory framework can contribute to this agenda. The goal of this agenda was primarily to improve access to sustainable energy for all, improve energy efficiency and to increase the share of renewable resources in a country's total energy generation mix. The overall aim of this dissertation is centred on how renewable energy resources can be harnessed to contribute towards the achievement of these targets.

1.3. Dissertation outline

The next chapters of this thesis report have been divided into the following; chapter 2 highlights the research objectives and the research hypothesis, chapter 3 presents the main methods used with regards to its novelty and contribution to the state of research, chapter 4 synthesizes and provide highlights of the key research findings based on the three scientific articles, and then the concluding chapter 5, highlights the limitations of the present study, and provides a summary of the implications of the research outcome on policy, as well as the way forward and finally propose gaps in the research that will require further studies.

2. Overarching goal of research

The overall goal of this research is to explore and quantify the potential of renewable energy resources in Ghana. This research is centred on and seeks to achieve two main objectives:

i. To provide sustainable energy for all by reaching the furthest as possible.
ii. To decarbonise the country's energy generation mix.

Thus, to achieve the objectives of this research, the viability of three selected renewable resources in Ghana have been evaluated in the three scientific articles using geospatial techniques and multi-criteria methods (see **Table 1** and **Appendix** for the three referenced articles). These renewable resources and technologies considered include:

a. Wind energy from a micro-wind turbine.
b. Solar energy from Photovoltaics (PV) and Concentrated Solar Power (CSP) systems.
c. Green hydrogen from solar PV and wind energy through the electrolysis process.

Table 1. Author's contribution to the three scientific papers

Scientific papers	Title	Publication journal	Author's contribution
Paper 1	Geospatial mapping of micro-wind energy for district electrification in Ghana	*Energy* in 2021 doi.org/10.1016/j.energy.2021.120217	Sole author (from conceptualisation to writing)
Paper 2	Optimal techno-economic potential and site evaluation for solar PV and CSP systems in Ghana. A geospatial AHP multi-criteria approach	*Renewable Energy Focus* in 2022 doi.org/10.1016/j.ref.2022.03.007	Sole author (from conceptualisation to writing)
Paper 3	Green hydrogen potential assessment in Ghana: application of PEM electrolysis process and geospatial-multi-criteria approach	*International Journal of Sustainable Energy* in 2023 doi.org/10.1080/14786451.2023.2256892	Sole author (from conceptualisation to writing)

It is also important to highlight that, despite the main goal of this research, the title sets the tone for the core argument of this research and the basis for the research hypothesis. The research tries to address some key challenges limiting the integration of renewable energies into the country's energy system by highlighting policy decisions that restrict the development and deployment of renewable energy in high potential areas. The study, hence, goes a step further to argue for grid electrification for rural or remote communities with high potentials, even if they do not meet all economic requirements for grid integration.

2.1. Research Hypothesis

Rural communities or remote locations that show high renewable energy generation capacities should be offered on-grid electrification to allow the use of their renewable energy potentials for the national development of Ghana, even if they do not meet all requirements for grid integration as set by the national energy policy as at present.

3. Methodology

Several methods have been applied in the literature to assess the potential of renewable energy resources for different case studies. However, the application of geospatial techniques combined with other methods have gained prominence over the years due to the spatial characteristics [20] of renewable resource availability as well as the scalability of the renewable energy generation capacities. This also refers to the uneven distribution of resources and this is where the application of GIS becomes valuable to help determine viable locations as well as help estimate the generation capacities at various scales, i.e., at microscale or macroscale levels. **Fig.1.** shows the conceptual framework used for this dissertation.

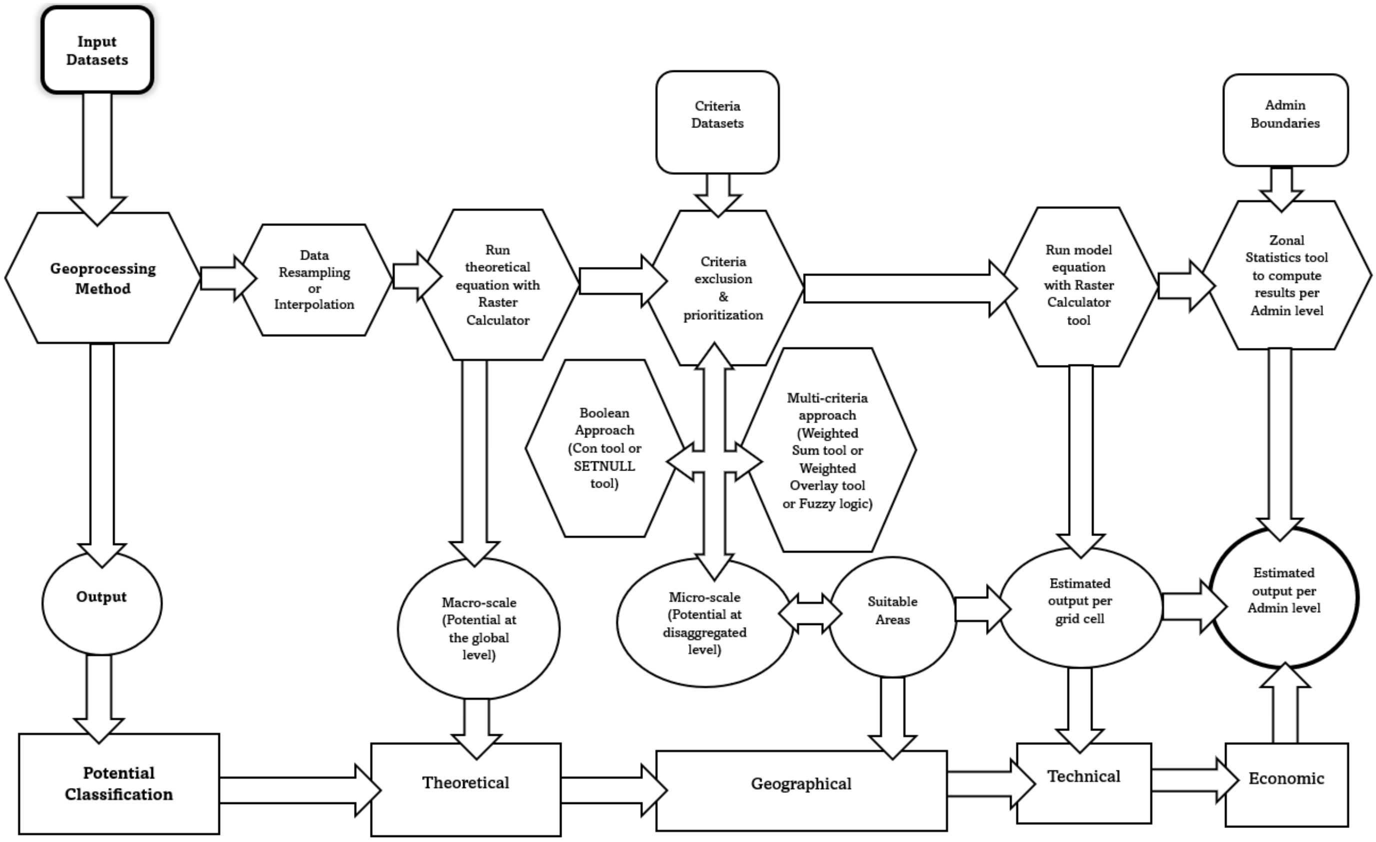


Fig. 1. Geospatial framework for resource potential assessment (in ArcGIS/ArcGIS Pro). Source: By Author.

3.1. Case study country— Ghana

Ghana is located in West Africa. The country shares its borders with Burkina Faso to the north, Togo to the east, Côte d'Ivoire to the west, and to the south, lies the Atlantic Ocean and the Gulf of Guinea. Total population as at 2021 was 30.8 million with an average household size of 3.6 [38]. **Fig. 2** shows the map of Ghana with the current administrative boundaries.

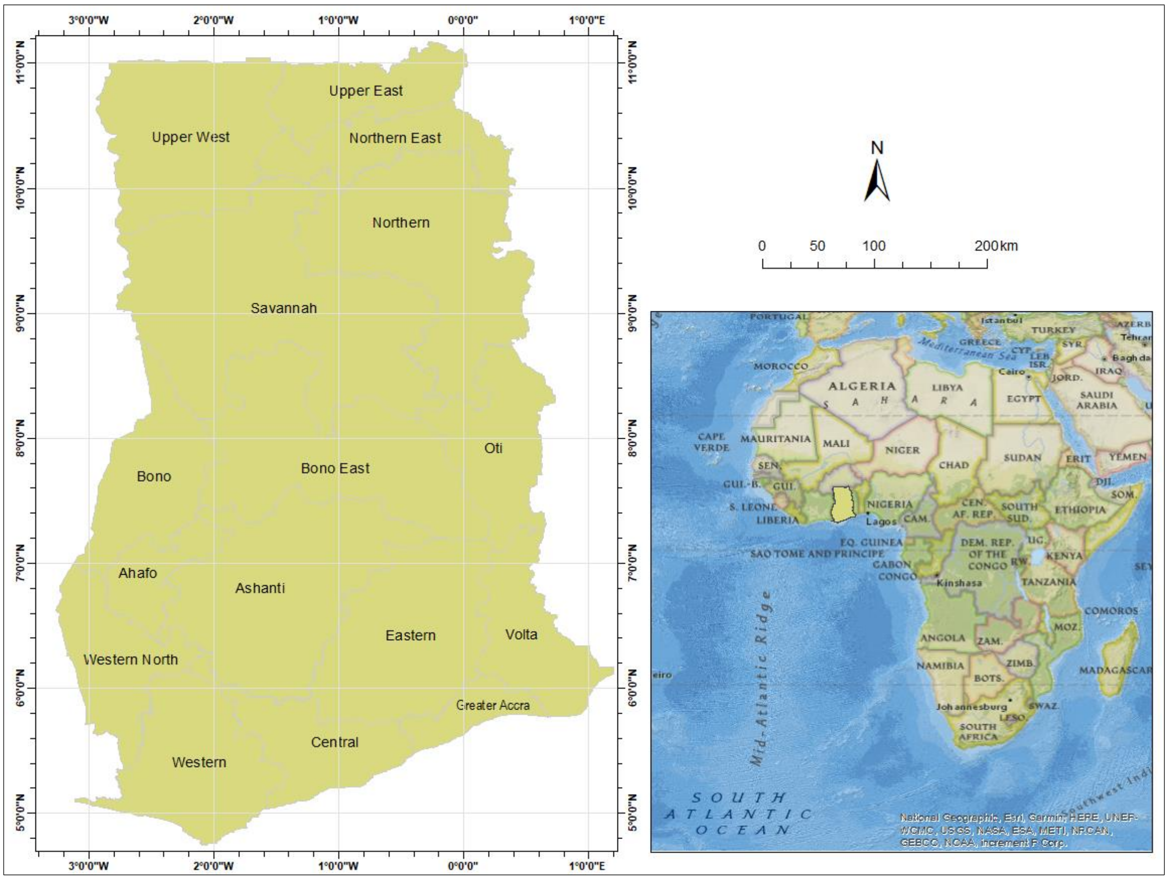


Fig. 2. Map of Ghana showing its geographical location. Map created by the Author. Data sources: [39, 40].

Further, as mentioned earlier, the research applied geospatial techniques, combined with two multi-criteria decision methods to quantify the potentials of the 3 selected renewable resources considered, these are; wind, solar from solar PV and CSP, and the production of green hydrogen from wind and solar PV. The methods included, the Boolean approach and the AHP methods. These two methods were used mainly to quantify the geographical potential. **Table 2** also shows the various resource potential categories considered in this research [19, 20, 41–43].

Table 2. Types of resource potential assessments applied

Category	Description
Theoretical potential[1]	The total global energy/power content of the energy resources.
Geographical potential	The total amount of land area available for the installation of the power plants considering geographical constraints.

[1] The theoretical potential analysis in this research was used mainly for the wind energy analysis and the production of green hydrogen from the wind power estimations. Please refer to research paper **1 [20]** and paper **3 [43].**

Technical potential	This is the mechanical energy generated at the geographical potential including energy losses by the power plant in the process of generating electricity from the power plants.
Economic potential	The technical potential that can be realised economically given the costs of conventional and the costs of alternative energy sources.

3.2. Theoretical resource potential assessment

The theoretical resource potential assessment, as mentioned earlier, was mainly used to estimate the general wind power density (WPD) potential of Ghana on a global scale— please refer to paper 1 [20] and paper 3 [43]. The equation used to estimate the WPD is given by:

$$\boldsymbol{WPD} = \frac{1}{2} * {}^{1}/_{n} * \sum_{j-1}^{n} \left(\rho_j * U_j^3\right) \quad (1)$$

where n is the number of wind speed observations and ρ_j and U_j are the j^{th} (1st, 2nd, 3rd, …etc.) observations of the air density [44] and wind speed respectively, per site.

3.3. Geographical resource potential assessment

The geographical potential involves an evaluation of the site, and it is basically an estimation of the total land area suitable for siting of the power plant to ensure optimal energy generation and operation of the selected power plant. Thus, locations that did not meet the suitability criteria were excluded from the analysis. For this research, protected areas [45] were completely excluded or restricted from the analysis. The geographical potential therefore forms the first reduction in the energy generation capacity of the site as parts of the land area were excluded from the rest of the potential estimations. The geographical potential can be estimated given the below equation:

$$S = \sum_{i=1}^{x} w_i C_i \prod_{j=0}^{y} R_j \quad (2)$$

where $\boldsymbol{S}$ is the site suitability value for mounting the wind turbine, $\boldsymbol{w_i}$ is the Boolean weight for the suitability criteria, $\boldsymbol{C_i}$ is the suitability criteria, and $\boldsymbol{R_j}$ is the restriction criteria.

Furthermore, to test the hypothesis of this research, certain key requirements that a community must meet to be eligible for grid integration or electrification according to the Ghana electrification policy were evaluated. The two main decision criteria and requirements included analysis of communities that are in close proximity to the power grid, for the case of Ghana, within a 20km buffer distance, and that the population density or customer density of the region or district should be above 500 persons per km^2 to be eligible for a connection to the grid [19, 46].

3.3.1. The Boolean approach

The Boolean method is a binary statistical method that involves the use of assigning two weights or vectors to decision criteria to determine their relative weights of importance. This method was used mainly to evaluate the site suitability parameters for the micro-wind assessment and for the green hydrogen potential assessment in the ArcGIS environment using the *Con tool* and *SETNULL tool*.

3.3.2. Analytic Hierarchy Process: The AHP method

The AHP method is a multi-criteria decision-making approach that helps to combine both quantitative and qualitative decision criteria to help solve complex problems related to energy planning. The AHP approach places decision criteria in hierarchical order to help illustrate the problem as well as help make judgements based on expert advice to derive a priority scale or scale of prominence. The AHP method was mainly used in the solar PV and CSP geographical estimations to help identify suitable areas for siting the power plants and deployment of the two selected solar technologies. It was applied to the research to help minimize the inconsistencies and uncertainties that may arise during the evaluation of the expert advice [22, 47]. Hence, a pairwise comparison matrix was designed to compute the consistency ratio ($\boldsymbol{CR}$) to help evaluate the degree of inconsistencies in the expert judgement on the decision criteria used. The pairwise matrix places value of importance on the decision criteria on a priority scale ranging from 1 to 9 to compare and describe the level of importance of a decision criterion. Where the value of 1 signifies *equal importance* and 9 represents *extreme importance* over the other decision criteria. Based on the number of decision criteria considered ($\boldsymbol{n}$) and given the two solar energy projects, a pairwise matrix was constructed, as illustrated in matrix ($\boldsymbol{A}$) below. Matrix ($\boldsymbol{A}$) will then represent a matrix where each entry a_{ij} of the matrix determines the level of importance of the i_{th} criterion to the j_{th} criterion as shown in the steps below [47]:

$$A = \begin{bmatrix} 1 & a & b \\ 1/a & 1 & c \\ 1/b & 1/c & 1 \end{bmatrix} \quad (3)$$

The next step after computing the pairwise comparison matrix was to examine the consistency of the matrix to minimize the perturbations that may occur in computing the eigenvector of a criterion. This is important because even though the levels of significance were assigned to a criterion based on expert opinion, expert opinions may be inconsistence and intransitive. Thus, the ***CR*** and the consistency index (***CI***) were estimated given the following equations [47]:

$$CR = CI/RI \quad (4)$$

$$CI = \frac{\lambda_{max - n}}{n - 1} \quad (5)$$

When **CR** < 0.1, the degree of consistency is acceptable, else the decision judgement is inconsistent when **CR** > 0.1 and thus will require revision of the pairwise matrices [47]. **Table 3** shows the value of the average consistency index or random index (***RI***) with the corresponding number of observed criteria (***n***).

Table 3. Values for ***RI*** with corresponding number of observed decision criteria (***n***).

n	2	3	4	5	9	7	8	9
RI	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45

It is important to mention that the decision criteria used in this research were not only based on best practices or expert opinions within the Sub-Saharan African region, but also based on the electrification policy of the country of study, Ghana. The criteria considered included the impact of slope or gradient of the terrain where the solar power plants will be mounted, the availability of water bodies, distance to major roads, the population density of the community, the closeness of the power plant to the central power grid systems, and more importantly the solar irradiance index (GHI for the PV system and DNI for the CSP system) recorded by the location as elaborated in **Table 4.** Proximity to the grid network and the population density were key criteria according to the Ghana electrification policy to determine the type of electrification solution to assign to the community, i.e., grid-tied system or off-grid solution—please see paper 2 [19].

Table 4. Decision criteria considered for the solar energy analysis (paper 2 [19])

Input criteria	Description	Source/Reference
Solar irradiance (GHI and DNI)	The annual mean solar intensity received by the location (kWh/m²/year).	GSA[48]
Slope	The gradient of the terrain must be ≤ 45° for the PV system and < 2.1° for the CSP system.	[49]
Roads	• Conventionally, the location where the power plant will be mounted must be accessible throughout all the project development phases, i.e., during preliminary site feasibility evaluation, plant installation, as well as during transmission and maintenance periods. • Additionally, helps to minimize total investment costs associated with transportation.	[50]
Grid infrastructure	• For grid integration purposes. • Also helps to determine the type of electrification solution to assign to the end-user. The closer the power plant is to the central grid, the greater the likelihood that communities in that location will be best serviced by grid-connection and vice versa for off-grid electrification when the power plant is sited farther away from the central grid.	[51]
Water bodies and rivers	This criterion was considered particularly to determine the availability and ease to access to water needed to cool the heat and to condense the steam cycle of the CSP thermal plant. To also help clean off dust that may have settled on the solar modules or panels.	[52]

Population density	• Was considered mainly to determine the optimal electrification solution to assign to the communities. • Helps to determine locations with less or more customer demand for the electricity or energy[2] produced.	[53]

3.4. Technical resource potential assessment

The technical potential as mentioned, basically refers to the amount of energy that the renewable energy power plants can produce over a period of time given the available land or geographical potential. This section therefore provides an overview of the methods and equations used to estimate the three selected renewable energies, i.e., wind energy (paper 1 [20]), solar PV and CSP systems (paper 2 [19]) as well as for the green hydrogen technologies (paper 3 [43]).

3.4.1. Wind energy technical potential estimation

For paper 1 [20], the wind energy potential estimation for this research was based on a single turbine model. To ensure that the selected turbine operates optimally, the wind turbine model, VESTAS 52/850 [54] micro-turbine with a cut-in wind speed requirement as low as 3.0 ms^{-1} and a cut-out wind speed of ~ 20 ms^{-1} was chosen to fit the nominal wind speed distribution in Ghana which ranges from ~ 1.0 ms^{-1} — ~ 9.8 ms^{-1} at a 50m hub height and thus, any wind turbine with higher wind speed requirements may need higher wind speed values to operate optimally and with this, a huge wind turbine with higher wind speed requirements may not be ideal considering the wind speed regime in Ghana. The power curve of this turbine was used to estimate the amount of wind energy that can be produced in a year per km^2 of land ($GWh/year/km^2$). It is also important to highlight that even though this turbine could be deployed on a large commercial scale, the main aim of this assessment (paper 1 [20]) in particular was to evaluate the potential of wind energy for residential electrification in Ghana at a more disaggregated level, at the district level on a 1km x1km resolution scale to understand the amount of wind energy that can be generated to meet the respective regional or district energy demands. The wind data was downloaded from the Global Wind Atlas (GWA) portal [55] .

Different methods have also been used to estimate the mechanical energy capacities of the turbine used and this is also based on the best fit simulation models used. For this study, not only was the turbine power curve used,

[2] Electricity or energy as used in the context of this research have been used interchangeably to refer to same.

but also the wind speed regime at the various locations were estimated to determine the potential of a site as well as the amount if wind energy the site can produce from the wind turbine used. To achieve this, the Weibull and Rayleigh probability distribution functions were compared. The Weibull function however provided the best-fit for the wind speed distribution in Ghana [20] (see paper 1). Hence, the Weibull distribution function was introduced into the turbine power curve equation to estimate the amount of mechanical energy that the turbine can generate in a year. The technical wind energy potential can thus be estimated by [20, 56]:

$$\overline{\mathrm{P}}_{\mathrm{w}}(U) = \int_{0}^{\infty} \mathrm{P}_{\mathrm{w}}(U)\,\mathrm{dF}(U) \tag{6}$$

Where $\overline{\mathrm{P}}_{w}(U)$ is the total wind energy produced by the turbine, $P_w(U)$ is the wind turbine power curve function, $\mathrm{dF}(U)$ represents the Weibull distribution function, and they can be estimated given the equations below [56]:

$$P_w(\mathrm{U}) = {}^{1}\!/_{2}\,\rho \mathrm{A} \mathrm{C}_{\rho} \mathrm{U}^3 \tag{7}$$

Where A is the swept area of the turbine rotor, which is $\approx \pi D^2/4$ (D is the rotor diameter and $\pi = 3.1416$), C_{ρ} is the dimensionless theoretical maximum power coefficient value of 0.59, ρ is the air density (kg/m^3; kilogram per cubic meter) and (U) is the wind speed value of the site. The Weibull function uses both the standard deviation and the mean values of the wind speed, and it is given as:

$$\mathrm{F}(U) = 1 - \exp\left[-\left(\frac{U}{c}\right)^{k}\right] \tag{8}$$

Where (U) is the wind speed of the site, c is the scale factor, and k is the shape factor, which are both parameters of the mean wind speed function and the standard deviation function.

3.4.2. Solar PV and CSP technical potential estimation

The ability of the selected solar power plants to function optimally usually also depends on the specifications and input requirements of the solar power plant. Different studies have included various parameters to model and estimate the amount of solar energy that the technology can produce per site in a year. However, for this study (paper 2 [19]), basic specifications required for the solar technology to function optimally was applied and these included the efficiency of the solar module, the solar radiation, the performance ratio (***PR***) of the PV system, as well as a land requirement ratio. The technology specifications and assumptions used were based on IRENA' 2020 report [57] as shown in **Table 5.** From the tiff GIS data used, the GHI in Ghana ranges from ~1 500 kWh/m²/year to ~2 080 kWh/m²/year and with the DNI ranging from ~700 kWh/m²/year to ~1 450 kWh/m²/year. The formulas used to estimate the solar PV and CSP systems are given as:

$$E_{pv} = [GHI * efficiency * PR] * [geographical\ potential/spacing\ factor] \quad (9)$$

$$E_{csp} = [DNI * efficiency] * [geographical\ potential/spacing\ factor] \quad (10)$$

Table 5. The solar PV and CSP systems specifications and assumptions

Specification	Solar PV system	CSP system
Technology type	Monocrystalline cells	Parabolic trough
Efficiency	15% — 22%	15% — 21%
Performance ratio (*PR*)	70% — 85%	—
Spacing factor	1.4 — 5	3 —7.5

3.4.3. Green Hydrogen technical potential estimation

Green hydrogen as the name suggests, refers to the production of hydrogen from renewable resources. This research (paper 3 [43]) explored the potential of generating hydrogen from solar and wind energy in Ghana. The technical potential in this context refers to the amount of green hydrogen that the electrolysis system can generate over the lifetime of the generating plant given the geographical potential. The production of hydrogen through electrolysis involves the process of splitting water into oxygen and hydrogen without emitting carbon dioxide into the atmosphere. Unlike the production of solar energy and wind energy, which involves a direct generation from the solar power plants and the wind turbine, respectively, green hydrogen production involves two separate generation processes. First, is the generation of the energy from the wind turbine or the solar PV system— please refer to sections **3.4.1.** and **3.4.2.** on how to estimate the technical potential for wind energy and solar energy, respectively, and then followed by the conversion system or the production of the generated energy into hydrogen using the electrolyser technology. Currently, there are two types of water electrolyser technologies which are the Proton Exchange Membrane (PEM) electrolyser and the Alkaline electrolyser [35, 58, 59] . For this research, the PEM electrolyser was preferred due to its efficiency, high lifecycle, and its compatibility with the variability of electricity generated from renewable sources [60, 61]. To estimate the technical potential of hydrogen that the PEM electrolyser system can produce from the wind turbine and the solar PV system, the following assumptions as shown in **Table 6** were used and given the below equations [59, 62]:

$$M_{H_2}\ of\ TP_{pv} = \frac{E_{H_2}}{HHV_{H_2}} = \frac{TP_{pv} * \eta_{Elec}}{HHV_{H_2}} \tag{11}$$

$$TP_{wind} = P_w(U) * \eta_{gb} * \eta_{gen} * \eta_{\phi} \tag{12}$$

$$\eta_{\phi} = \frac{Geographical\ potential}{spacing\ value * rotor\ diameter} \tag{13}$$

$$M_{H_2}\ of\ TP_{Wind} = \frac{E_{H_2}}{HHV_{H_2}} = \frac{TP_{Wind} * \eta_{Elec} * \eta_{Rec}}{HHV_{H_2}} \tag{14}$$

TP_{pv} and TP_{wind} represent the solar and wind energy conversion systems, respectively, and E_{H_2} is the electricity requirement for the power plant. η_{Rec} represents the rectifier efficiency, η_{Elec} is the efficiency of the electrolysis system, and HHV_{H_2} is the hydrogen higher heating value, and η_{ϕ} is the spacing factor which varies and depends on the land size of the suitable area per region.

Table 6. Green hydrogen technical specifications and assumptions

Component	**Value**
Photovoltaic module efficiency ($\boldsymbol{\eta_{PV}}$)	17.5%
Power conditioning efficiency ($\boldsymbol{\eta_{PC}}$)	85%
Electrolysis system efficiency ($\boldsymbol{\eta_{Elec}}$)	75%
Rectifier efficiency ($\boldsymbol{\eta_{Rec}}$)	90 %
Hydrogen Higher Heating value ($\boldsymbol{HHV_{H_2}}$)	39.4 kWh/kg
Gearbox efficiency ($\boldsymbol{\eta_{gb}}$)	85%
Generator efficiency ($\boldsymbol{\eta_{gen}}$)	95%
Wind turbine spacing factor ($\boldsymbol{\eta_{\phi}}$)	Vary

3.5. Economic resource potential assessment

To estimate the economic potential of the renewable energy produced, the levelized cost of energy (LCOE) method was used. The LCOE method was used to estimate the unit price of solar energy generated from the solar PV system and CSP system given. It is used as a measure to compare the lifecycle costs of generating electricity from different generation plants or technologies and includes components such as the initial investment or capital costs, the operations and maintenance costs (O&M), and the discount rate, just to mention a few [63, 64]. The costs components and assumptions used in this research were based on IRENA' 2020 renewable power generation cost report [57]. The economic potential assessment was mainly considered in the solar resource potential assessment study (refer to paper 2 [19]). The formular used to compute the LCOE is given as [63]:

$$LCOE = \left(\sum_{t=1}^{n} \frac{I_t + O\&M_t}{(1 + r)^t}\right) \Bigg/ \left(\sum_{t=1}^{n} \frac{E_t}{(1 + r)^t}\right) \tag{15}$$

where, $LCOE$ is the average lifetime levelized cost of the energy produced, I_t is initial capital costs in the year (*t*), $O\&M_t$ is the operations and maintenance costs in the year *t*, E_t is the amount of energy produced by the power plant in the year *t*, r is discount rate, and n represents the lifetime of the system.

4. Results and Key Findings

This section presents the key findings and highlights of the three research papers as well as to provide proof for making a case for the core argument of this dissertation. Results of the research have therefore been summarised and presented with the associated results visualisation to mainly address the hypothesis of this study. As mentioned earlier, the core hypothesis of this research is that it is more beneficial for Ghana's economy to serve grid electrification to rural communities with high renewable energy generation capacities than to provide them with off-grid electrification. Two key assumptions and criteria requirements for on-grid electrification based on the electrification policy of Ghana were applied, and these include but are not limited to the population density of the location or the number of persons in a location and their proximity to the grid network [46]. Key highlights of the research findings based on these grid integration decision criteria are discussed here.

4.1. Theoretical potential

The theoretical potential, as mentioned earlier broadly refers to the amount of energy that can be harnessed on a global scale or on a large macro-scale. It usually does not include an assessment of the local conditions and other factors that can impact the energy output of the power plant. The theoretical potential is useful in providing an overview or insight into the energy potential of a location. For this research, the theoretical potential was mainly applied to the wind energy potential assessment (see paper 1 [20]). Based on the extrapolation assessment, a wind speed distribution of about 1.0 ms^{-1} — 9.8 ms^{-1} can be recorded in Ghana given a wind turbine hub height and anemometer height of above 50m. The wind power density of the location was used to estimate the global power potential of the wind speed distribution across all locations in the country as shown in **Fig.3.** Results from the analysis showed varying potentials, ranging from the lowest of ~ 38.97 W/m² to ~ 1, 070.24 W/m² maximum across the districts or regions in Ghana. On a global scale, the country recorded a WPD of ~ 0.04MW/km².

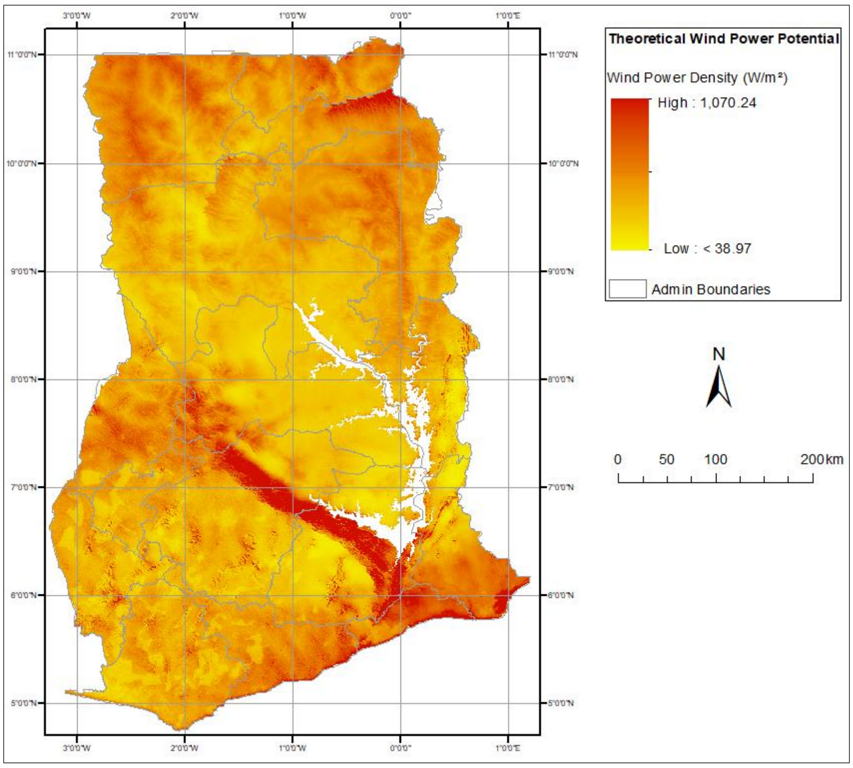


Fig. 3. Theoretical potential based on the Wind Power Density estimates. Map created by the Author. Data sources: [39, 55].

4.2. Geographical potential

Secondly, the geographical potential was used to evaluate the suitability of the topography or terrain conditions necessary to ensure the optimal operation of the chosen power plant. This assessment is particularly relevant and forms an integral part of the renewable resource potential assessment as it provides insights into the climatic requirements of the renewable resources and the characteristics of the topography of the site. Also, the geographical potential may also include an assessment of the local energy policies that may or may not allow for the siting of the power plant at a specific location. Therefore, for this research, the geographical potential assessment was applied to all three resource technologies considered, i.e., the wind turbine, the solar PV and CSP systems, and for the green hydrogen technologies (energy conversion systems and the electrolyser). It is however important to mention that the geographical potential is directly influenced by the administrative boundary (polygon area) used for the evaluation and thus any reduction or elimination of any part of the administrative boundary of a location will directly affect the geographical potential. And, as discussed earlier, the geographical potential forms the first reduction in the amount of energy that the power plant can produce given the available or suitable land areas. From the administrative boundary used, the total land area of Ghana is ~ 238,723km², with about 33,000km² to 34,000km² restricted or unsuitable area of land; and with about 85%—86% geographical potential for all the renewable energy resources considered, as shown in **Fig. 4.**

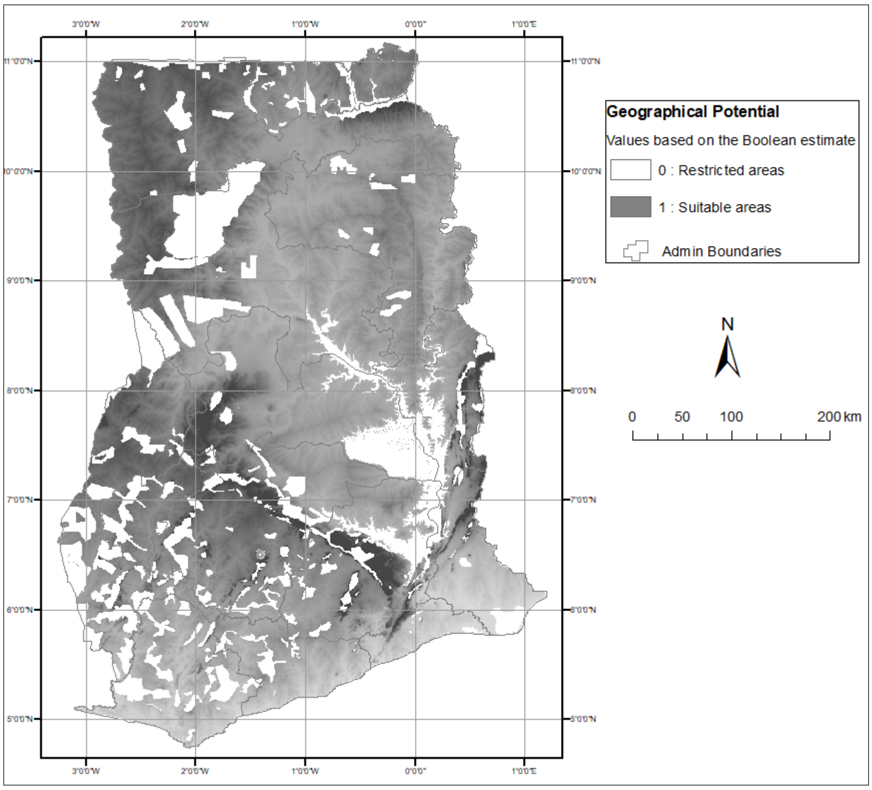
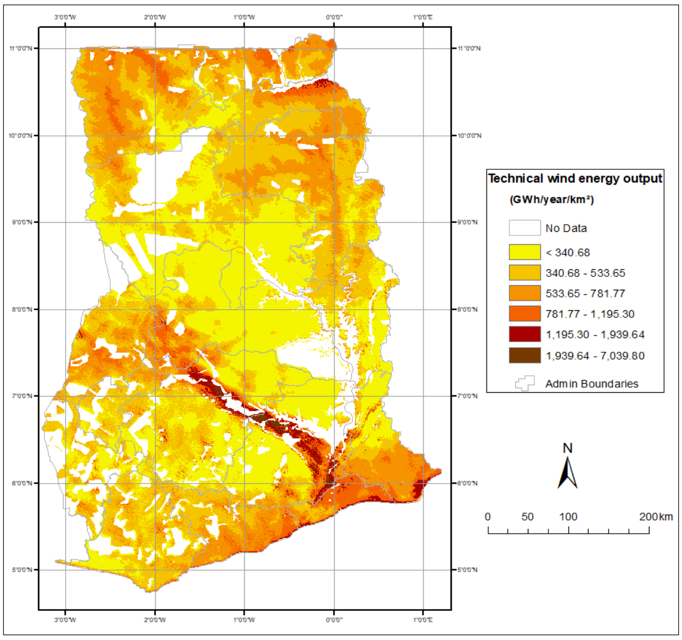


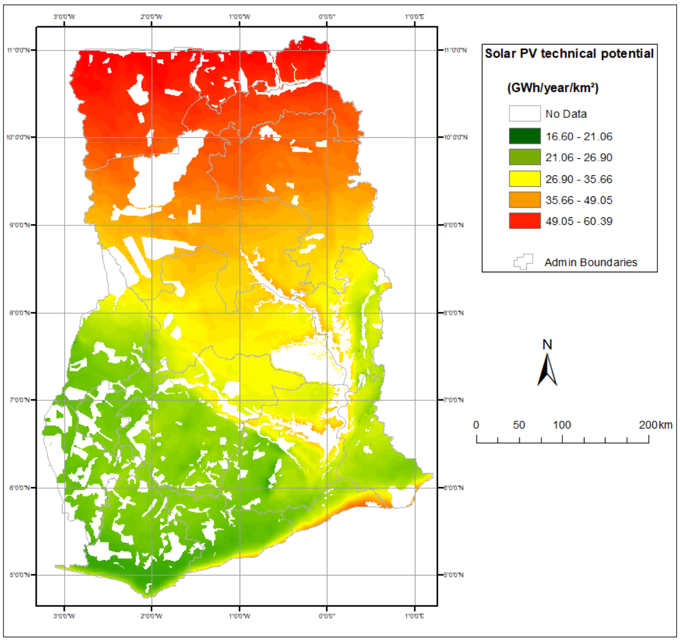
Fig. 4. Geographical potential for all 3 resource assessments. Map created by the Author. Data source: [39].

4.3. Technical potential

For the technical potential, the amount of mechanical energy that the selected power plants can produce at a location given the geographical potential have been presented for the three renewable resource technologies under consideration. Also, just like the geographical potential, the technical potential recorded varying generation capacities across all locations in Ghana. And, as earlier discussed, this research is based on a 1km x 1km grid cell analysis and also, results of the assessments are based on the key assumptions and criteria used. It is therefore important to highlight that, results may defer if different decision criteria and assumptions are applied. However, the total national estimates represent the sum of all regional outputs per technology type. For the wind energy assessment, a total of ~ 300TWh of wind energy can be harnessed annually in the country. At the regional level, areas with higher generation capacities, i.e., mountainous areas, the Eastern, and the Ashanti regions recorded over 2,000GWh/km^2/year (see **Fig.5.a**), including some areas along the coast which have been the focus of many of the wind energy pilot projects. However, from the on-grid electrification potential evaluation, communities within some high generation potential areas like Adaklu-Anyigbe in the Volta region and the Sekyere-Afram Plains in the Ashanti region will not be considered for grid integration due to their low customer demand of about 8GWhy^{-1} which is because of their low population density, and distance from the proximity grid threshold even though these areas could generate over 3,000 GWh/km^2 of wind energy per annum [20] (please refer to paper 1).

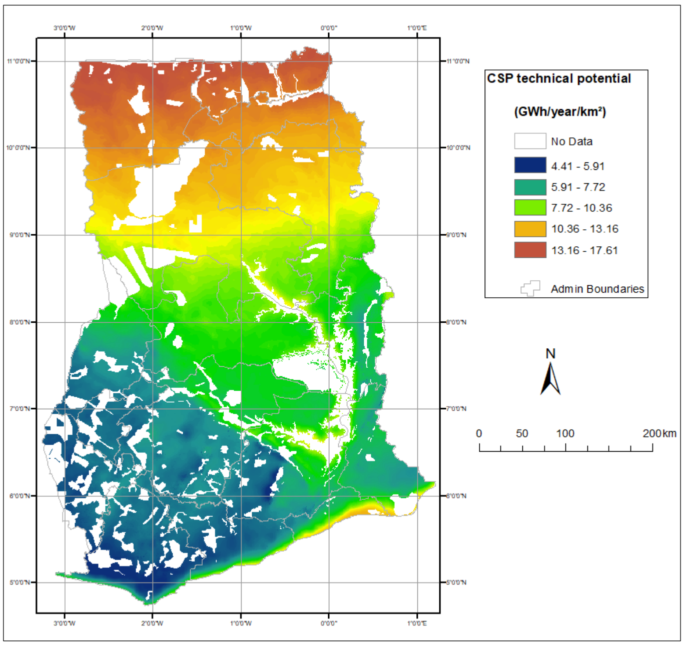
Further, results from the solar energy analysis also show that about 68,622TWh of energy can be generated from the solar PV system per year, and about 23,453 TWh/year from the CSP system. Here also, from the visualisation and analysis (see **Fig. 5.b** and **5.c**), it can be observed that, the communities in the northern parts of the country recorded the highest generation capacities ~49 GWh/km^2 — 60 GWh/km^2 for the PV system and from ~ 13GWh/km^2 —18GWh/km^2 for the CSP system. The Upper West region alone recorded a technical suitability of 56.33% for the PV system and ~55.50% for the CSP system, yet due to the region's low population density and distance from the 20km grid proximity threshold may not qualify for grid electrification (see paper 2 [19]) but rather off-grid, thereby hindering the ability of the country to accelerate the decarbonisation of its energy system, which is currently predominantly fossil based [16]. Basically, the misconception in the present grid connection rules is that the present electrification policy looks at grid connection only from an electricity supply perspective for the regions, it simply does not take into account the vast electricity generation potential in the remote areas, which have the resources to supply Ghana with abundant cheap renewable energy.





a. Energy output from the wind turbine system.

b. Energy output from the solar PV system.



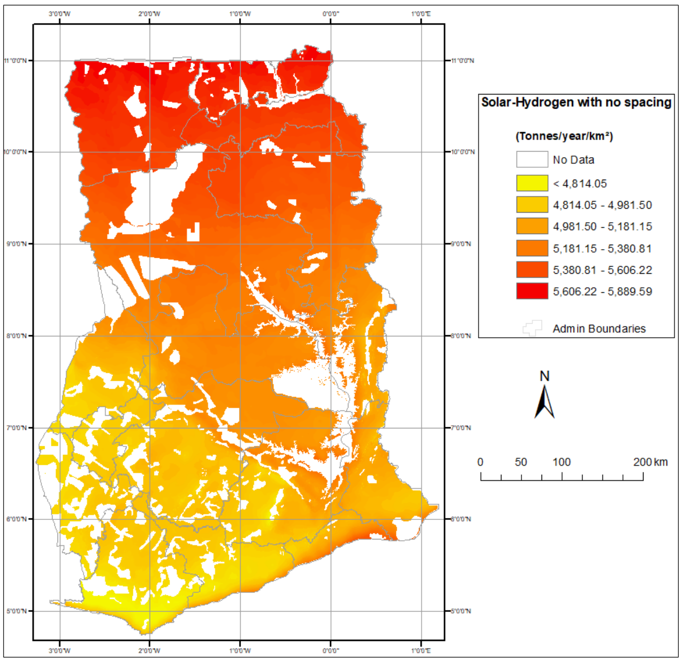
c. Energy output from the CSP system.

Fig. 5. Technical potential for the wind, and solar (PV and CSP) resources. Maps created by the Author. Data sources: [39, 48, 55].

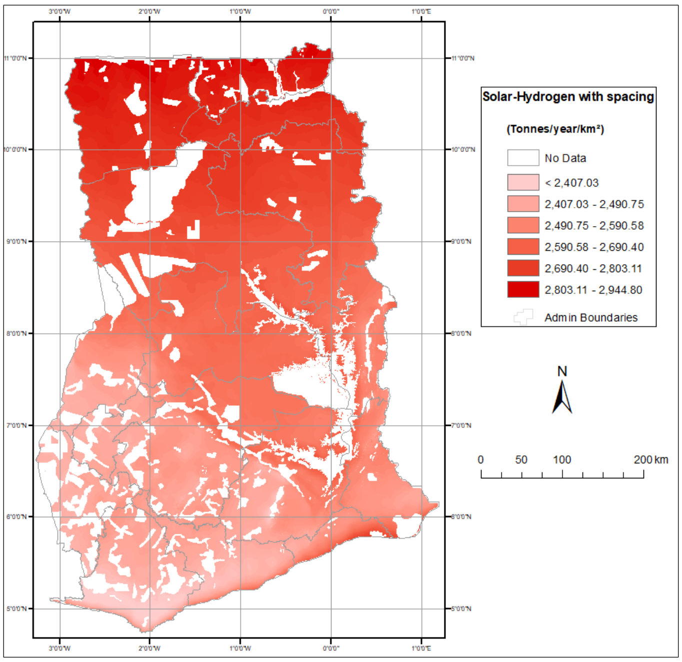
Additionally, at the national level, results from the green hydrogen assessment showed that, about 10,123.36 Mt[3] of wind hydrogen can be harnessed annually in the country and about 14,196.21 Mt/year from the solar hydrogen systems, with no spacing constraints (please refer to summary table in paper 3 [43]). Here also, despite that fact that the northern part of the country recorded the highest potential for the solar hydrogen, many of the

[3] Million tonnes

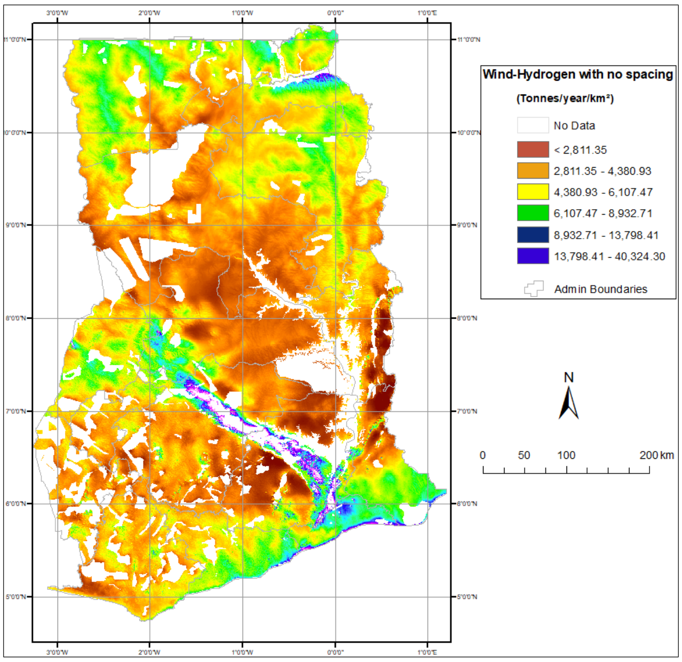
communities did not qualify for on-grid electrification due the remoteness of these locations and the low population density (see **Fig.6.**and **6.b**). The same applies to some locations in the Eastern and Volta regions when it comes to the wind hydrogen generation capacities, as visualised in **Fig.6.c** and **6.d**.



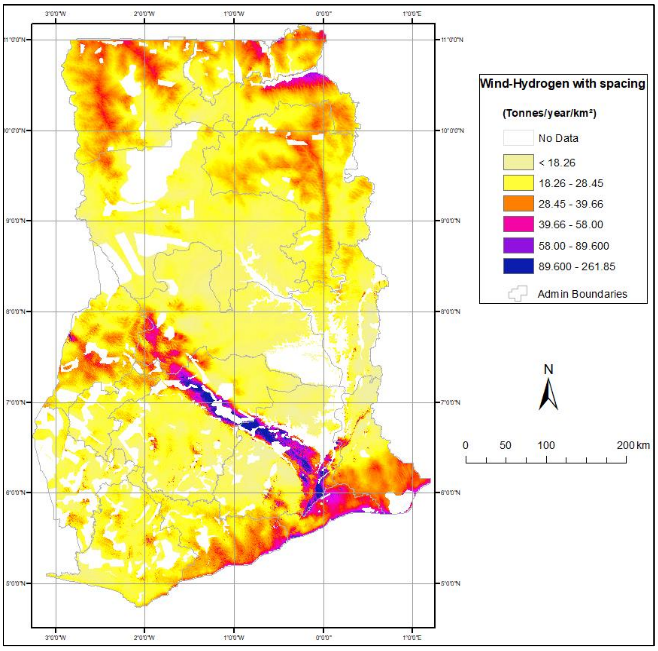
a. Hydrogen mass (H_2) from the solar PV conversion system with no spacing.



b. Hydrogen mass (H_2) from the solar PV conversion system with spacing.



c. Hydrogen mass (H_2) from the wind conversion system with no spacing.

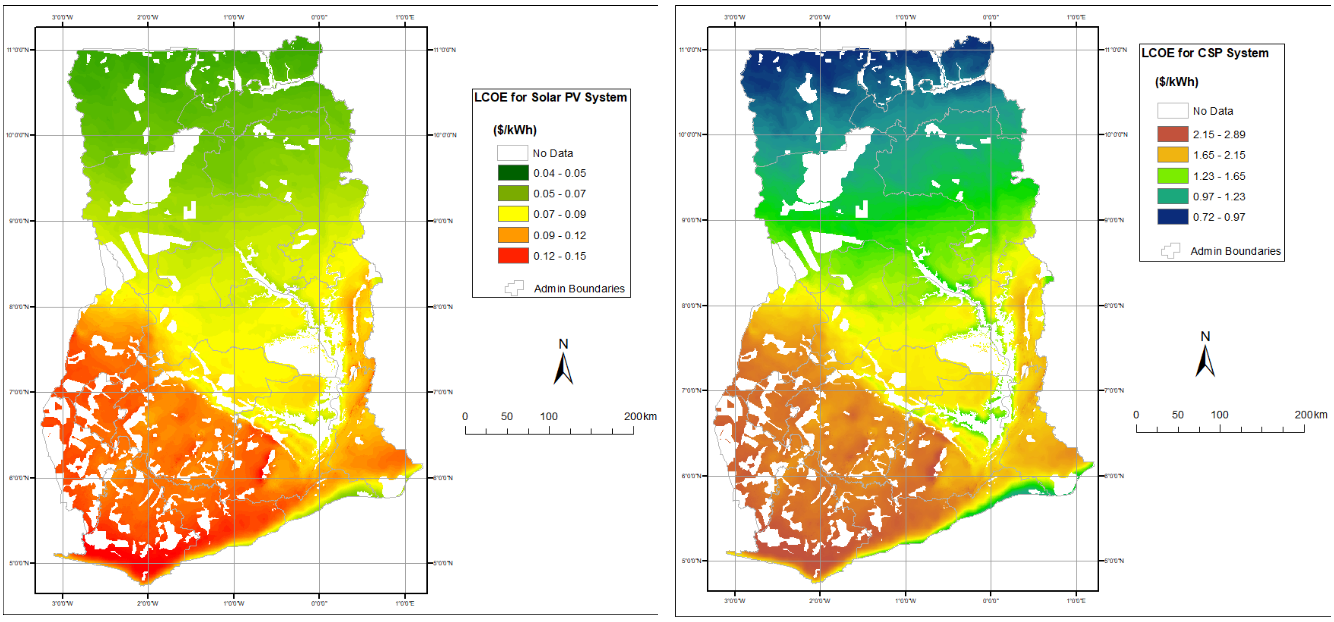


d. Hydrogen mass (H_2) from the wind conversion system with spacing.

Fig. 6. Technical potential for the green hydrogen production using solar and wind. Maps created by the Author. Data sources: [39, 48, 55].

4.4. Economic potential

The economic potential assessment as discussed earlier, was performed only for the solar PV and the CSP system by estimating the LCOE for the two solar energy technologies (please refer to paper 2 [19]). From the analysis, the LCOE for the solar PV system ranges from about \$0.04/kWh — \$0.15/kWh, and from \$0.72/kWh — \$2.89/kWh for the CSP system in the country as shown in **Fig.7.** It can also be observed that, the LCOE estimates show a direct correlation to the technical energy generation capacities across the various sites, with the northern part and a narrow strip along the coast showing the best potential areas for investment into solar energy projects due to the optimal unit costs for both the PV and the CSP systems.



a. LCOE for the solar PV technology. b. LCOE for the CSP technology.

Fig. 7. Economic potential for the solar PV and CSP systems. Maps created by the Author. Data sources: [39, 48, 55].

5. Conclusion

This section provides a general overview of the research findings and their implications for policy towards the achievement of sustainable universal energy access by reaching the furthest as possible and to enhance energy systems decarbonisation in Ghana, and by extension contribute to the global call to limit global warming to

1.5°C. This also includes a validation assessment of the hypothesis of this research. Results from the research show varying resource potentials across the country. This case study research, as discussed, applied a geospatial-multi-criteria approaches to quantify the potential of solar energy, wind energy and the potential to produce green hydrogen from solar PV and wind at various scales across the country. Results from the assessment reinforce the core argument of this research in that, for instance, the solar energy potential analysis shows that in the northern part of the country, even though having the largest capacities for both the solar PV and CSP systems, many communities will be assigned off-grid electrification status instead of grid electrification. This is because, as per the current electrification policy of the country, communities in these areas do not meet all the requirements for on-grid electrification due to their low population densities and distance from the existing grid infrastructure. The isolated demand orientation in the present grid connection rules do not take into account the vast electricity generation potential in the remote areas, which have the resources to supply Ghana with abundant cheap renewable energy.

The results of the analysis show that decarbonization of the country's energy system can be significantly advanced when renewable energy integration is viewed more from a perspective of renewable energy supply from all regions in Ghana, as well as from the perspective of the end-user through grid integration. This will therefore imply that an increase in grid-connected renewable electrification will translate into increased access to sustainable energy due to the increase in the supply of renewable energy in the total generation mix. Thus, the use of the more remote solar and wind energy potentials of Ghana combined with a strategy of more aggressive grid connection of remote areas rich in renewable resources can achieve both an increase in electricity access of the entire population of Ghana and a fast and just transition to a carbon free electricity supply for the country.

5.1. Limitations of the dissertation

A major limitation of this research is the adoption of a case study approach that primarily focuses on a particular country in Africa, Ghana. By this approach, all the assumptions and data used are informed by the conditions in the country and thus, the proposed framework and the outcome of the three scientific articles may not apply to countries in different geographies and or may require different parameters.

In addition, large scale development and deployment of energy transition projects, especially in remote areas or of the grid areas are usually capital intensive and may require substantial financial investment to implement these projects. However, despite the seeming capital intensiveness, these rural or remote locations are likely to enjoy economies of scale with multiplier effects in the long term due to the benefits associated with infrastructure development such as the expansion of the grid network to these high potential rural areas, as well as anticipated employment opportunities, and urbanization, just to mention a few.

5.2. Policy Implications and the Way Forward

The researcher thus proposes the following strategies as the way forward towards sustainable universal energy access and energy systems decarbonisation:

a. **Investment** into renewable energy projects must be **intentiona**l and **targeted** to scale-up deployment and accelerate integration.
b. Identify and set priority projects to help fulfil climate goals and meet climate targets.
c. Subsidies on private low-carbon projects and investor-friendly green policies, and
d. Scale-up feasibility studies.
e. According to the SDG 7.b, there must also be a conscious effort to "*expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all in developing countries"* by 2030 [17].
f. Extend the north-south high voltage power lines to supply the load centres of Ghana with renewable electricity from the northern regions.
g. Mobilize international climate funding to finance the necessary infrastructure investments for the necessary expansion of Ghana's renewable energy supply.

5.3. Reflections on progress made in the current state of research and recommendations for further studies

a. A review of current discourses in the literature shows the production of green hydrogen as gaining increasing attention as a viable renewable energy resources that will require further investigation in terms of its development and deployment as well as its competitiveness in the global renewable energy market.
b. A gap in this dissertation that will also require further studies and also drawing attention particularly in informing energy policy, is how to estimate the social dimension of energy transition projects. Even though the present study considered the role of the national energy policy, further studies to explore how

GIS can be used to estimate the impact of other social perspectives like the impact of local community policies on energy transition projects will thus be valuable.

References

[1] UN, *What Is Climate Change? | United Nations.* [Online]. Available: https://www.un.org/en/climatechange/what-is-climate-change (accessed: Aug. 9 2023).

[2] IEA, *Climate change: Energy sector is central to efforts to combat climate change*. [Online]. Available: https://www.iea.org/topics/climate-change (accessed: Aug. 9 2023).

[3] UN, "*Resolution adopted by the General Assembly [on the report of the Second Committee (A/65/436 and Corr.1)]:65/151. International* Year of Sustainable Energy for All. https://undocs.org/A/RES/65/151," 2011. [Online]. Available: https://documents-dds-ny.un.org/doc/UNDOC/GEN/N10/521/60/IMG/N1052160.pdf?OpenElement

[4] UN-AGECC, "Energy for a sustainable future: *Report and recommendations.* New York," 2010. [Online]. Available: https://www.un.org/millenniumgoals/pdf/AGECCsummaryreport[1].pdf

[5] IPCC, "Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.," 2018. [Online]. Available: https://www.ipcc.ch/site/assets/uploads/sites/2/2022/06/SR15_Full_Report_HR.pdf

[6] IRENA, *Renewable Power Generation Costs in 2021.* [Online]. Available: https://www.irena.org/publications/2022/Jul/Renewable-Power-Generation-Costs-in-2021 (accessed: Jul. 14 2023).

[7] M. Georgati, J. Monteiro, B. Martins, and C. Keßler, "Spatial Disaggregation of Population Subgroups Leveraging Self-Trained Multi-Output Gradient Boosting Regression Trees," *AGILE GIScience Ser.*, vol. 3, pp. 1–14, 2022, doi: 10.5194/agile-giss-3-5-2022.

[8] CCAFS & CGIAR, *Spatial Disaggregation.* [Online]. Available: https://www.ccafs-climate.org/spatial_disaggregation/ (accessed: Aug. 9 2023).

[9] World Health Organization, "Energizing health: accelerating electricity access in health-care facilities," 14 Jan., 2023. https://www.who.int/publications/i/item/9789240066960 (accessed: Jul. 13 2023).

[10] UNICEF, “A brighter life for every child with sustainable energy,” 2022. [Online]. Available: https://www.unicef.org/media/127626/file/A%20brighter%20life%20for%20every%20child%20with%20sustainable%20energy.pdf

[11] Energia, *Research Project 7: Building the Evidence Base for Women's Empowerment and Entrepreneurship to Improve Energy Interventions' Effectiveness - Energia.* [Online]. Available: https://www.energia.org/project/building-the-evidence-base-for-womens-empowerment-and-entrepreneurship/ (accessed: Feb. 16 2021).

[12] UNDP, *Energy and Gender Equality | United Nations Development Programme.* [Online]. Available: https://www.undp.org/energy/our-work-areas/energy-and-gender-equality (accessed: Jul. 13 2023).

[13] IEA, IRENA, UNSD, World Bank, WHO, “Tracking SDG 7:The Energy Progress Report. World Bank, Washington DC. © World Bank. License: Creative Commons Attribution—Non-Commercial 3.0 IGO (CC BY-NC 3.0 IGO).,” 2023. [Online]. Available: https://trackingsdg7.esmap.org/data/files/download-documents/sdg7-report2023-full_report.pdf

[14] IEA, *World Energy Outlook 2022 – Analysis - IEA.* [Online]. Available: https://www.iea.org/terms/creative-commons-cc-licenses (accessed: Jul. 6 2023).

[15] IEA, IRENA, UNSD, World Bank, WHO, *Ghana | Tracking SDG 7.* [Online]. Available: https://trackingsdg7.esmap.org/country/ghana (accessed: Jul. 6 2023).

[16] Energy Commission of Ghana, “2021 Energy Outlook for Ghana: Demand and Supply Outlook,” 2021. [Online]. Available: http://www.energycom.gov.gh/planning/data-center/energy-outlook-for-ghana

[17] United Nations, *Energy - United Nations Sustainable Development.* [Online]. Available: https://www.un.org/sustainabledevelopment/energy/ (accessed: Jul. 6 2023).

[18] Energy Commission of Ghana, “Ghana Renewable Energy Master Plan,” 2019.

[19] M. Asare-Addo, “Optimal techno-economic potential and site evaluation for solar PV and CSP systems in Ghana. A geospatial AHP multi-criteria approach,” *Renewable Energy Focus*, vol. 41, pp. 216–229, 2022, doi: 10.1016/j.ref.2022.03.007.

[20] A.-A. Mary, “Geospatial mapping of micro-wind energy for district electrification in Ghana,” *Energy*, vol. 225, p. 120217, 2021, doi: 10.1016/j.energy.2021.120217.

[21] Y. Choi, J. Suh, and S.-M. Kim, “GIS-Based Solar Radiation Mapping, Site Evaluation, and Potential Assessment: A Review,” *Applied Sciences*, vol. 9, no. 9, p. 1960, 2019, doi: 10.3390/app9091960.

[22] H. Z. Al Garni and A. Awasthi, “Solar PV power plant site selection using a GIS-AHP based approach with application in Saudi Arabia,” *Applied Energy*, vol. 206, pp. 1225–1240, 2017, doi: 10.1016/j.apenergy.2017.10.024.

[23] F. Ali, A. Bennui, S. Chowdhury, and K. Techato, “Suitable Site Selection for Solar-Based Green Hydrogen in Southern Thailand Using GIS-MCDM Approach,” *Sustainability*, vol. 14, no. 11, p. 6597, 2022. [Online]. Available: https://www.mdpi.com/2071-1050/14/11/6597

[24] H. E. Colak, T. Memisoglu, and Y. Gercek, “Optimal site selection for solar photovoltaic (PV) power plants using GIS and AHP: A case study of Malatya Province, Turkey,” *Renewable Energy*, vol. 149, pp. 565–576, 2020, doi: 10.1016/j.renene.2019.12.078.

[25] J. R. Doorga, S. D. Rughooputh, and R. Boojhawon, “Multi-criteria GIS-based modelling technique for identifying potential solar farm sites: A case study in Mauritius,” *Renewable Energy*, vol. 133, pp. 1201–1219, 2019, doi: 10.1016/j.renene.2018.08.105.

[26] A. Gerbo, K. V. Suryabhagavan, and T. Kumar Raghuvanshi, “GIS-based approach for modeling grid-connected solar power potential sites: a case study of East Shewa Zone, Ethiopia,” *Geology, Ecology, and Landscapes*, vol. 6, no. 3, pp. 159–173, 2022, doi: 10.1080/24749508.2020.1809059.

[27] J. R. Janke, “Multicriteria GIS modeling of wind and solar farms in Colorado,” *Renewable Energy*, vol. 35, no. 10, pp. 2228–2234, 2010, doi: 10.1016/j.renene.2010.03.014.

[28] International Renewable Energy Agency (IRENA), “Estimating the Renewable Energy Potential in Africa: A GIS-based approach,” *Renewable Energy*.

[29] A. Yushchenko, A. de Bono, B. Chatenoux, M. Kumar Patel, and N. Ray, “GIS-based assessment of photovoltaic (PV) and concentrated solar power (CSP) generation potential in West Africa,” *Renewable and Sustainable Energy Reviews*, vol. 81, pp. 2088–2103, 2018, doi: 10.1016/j.rser.2017.06.021.

[30] T. Huang, S. Wang, Q. Yang, and J. Li, “A GIS-based assessment of large-scale PV potential in China,” *Energy Procedia*, vol. 152, pp. 1079–1084, 2018, doi: 10.1016/j.egypro.2018.09.126.

[31] T. Huld, R. Müller, and A. Gambardella, “A new solar radiation database for estimating PV performance in Europe and Africa,” *Solar Energy*, vol. 86, no. 6, pp. 1803–1815, 2012, doi: 10.1016/j.solener.2012.03.006.

[32] M. S. Adaramola, M. Agelin-Chaab, and S. S. Paul, *Assessment of wind power generation along the coast of Ghana*, 2014. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0196890413005426/pdfft?isDTMRedir=true&download=true

[33] D. Kline, D. Heimiller, and S. Cowlin: NREL, "GIS Method for Developing Wind Supply Curves," [Online]. Available: https://www.nrel.gov/docs/fy08osti/43053.pdf

[34] R. Bhandari, "Green hydrogen production potential in West Africa – Case of Niger," *Renewable Energy*, vol. 196, pp. 800–811, 2022, doi: 10.1016/j.renene.2022.07.052.

[35] T. R. Ayodele and J. L. Munda, "Potential and economic viability of green hydrogen production by water electrolysis using wind energy resources in South Africa," *International Journal of Hydrogen Energy*, vol. 44, no. 33, pp. 17669–17687, 2019, doi: 10.1016/j.ijhydene.2019.05.077.

[36] E. Fernandez-Vazquez, A. Diaz Dapena, F. Rubiera-Morollon, and A. Viñuela, "Spatial Disaggregation of Social Indicators: An Info-Metrics Approach," (in En;en), *Soc Indic Res*, vol. 152, no. 2, pp. 809–821, 2020, doi: 10.1007/s11205-020-02455-z.

[37] UNFCCC, *Nationally Determined Contributions (NDCs).* [Online]. Available: https://unfccc.int/process-and-meetings/the-paris-agreement/nationally-determined-contributions-ndcs/nationally-determined-contributions-ndcs (accessed: Feb. 17 2021).

[38] Ghana Statistical Service, "Ghana 2021 population and housing census. General report.," Volume 3A, 2021. [Online]. Available: https://census2021.statsghana.gov.gh/

[39] OCHA & Humanitarian Data Exchange (HDX), *Ghana - Subnational Administrative Boundaries.* [Online]. Available: https://data.humdata.org/dataset/cod-ab-gha (accessed: 2023).

[40] Esri, *National Geographic World Map.* [Online]. Available: https://www.arcgis.com/home/item.html?id=b9b1b422198944fbbd5250b3241691b6 (accessed: Aug. 2 2023).

[41] M. Hoogwijk, B. de Vries, and W. Turkenburg, "Assessment of the global and regional geographical, technical and economic potential of onshore wind energy," *Energy Economics*, vol. 26, no. 5, pp. 889–919, 2004, doi: 10.1016/j.eneco.2004.04.016.

[42] A. Wijk, J. P. Coelingh, and Stichting Energieonderzoek Centrum Nederland. Rijksuniversiteit te Utrecht., *Wind power potential in the OECD countries*. Utrecht the Netherlands: Department of Science Technology and Society Utrecht University, 1993. [Online]. Available: http://worldcatlibraries.org/wcpa/oclc/262847400

[43] M. Asare-Addo, "Green hydrogen potential assessment in Ghana: application of PEM electrolysis process and geospatial-multi-criteria approach," *International Journal of Sustainable Energy*, vol. 42, no. 1, pp. 1202–1225, 2023, doi: 10.1080/14786451.2023.2256892.

[44] M. Asare-Addo, *Air Density - GHANA: Mendeley Data, V1* (accessed: Feb. 17 2021).

[45] UNEP-WCMC and IUCN, *Protected Planet: The World Database: Protected Areas (WDPA)*, 2021. [Online]. Available: www.protectedplanet.net

[46] Ghana – Action Plan for Sustainable Energy for All by 2030, "SE4ALL-GHANA ACTION PLAN,"

[47] Thomas L. Saaty, *The analytic process: planning, priority setting, resources allocation*, 1980. [Online]. Available: https://scholar.google.com/citations?user=mcapoueaaaaj&hl=en&oi=sra

[48] Global Solar Atlas, *Global Solar Atlas 2.0, a free, web-based application is developed and operated by the company Solargis s.r.o. on behalf of the World Bank Group, utilizing Solargis data, with funding provided by the Energy Sector Management Assistance Program (ESMAP). For additional information: https://globalsolaratlas.info.* [Online]. Available: https://globalsolaratlas.info/map?c=7.972198,-1.032715,7&r=GHA (accessed: Mar. 29 2023).

[49] Global Terrain Slope and Aspect Data, *IIASA - Land Use Change and Agriculture Program.* [Online]. Available: http://webarchive.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML/global-terrain-slope-download.html?sb=7 (accessed: Jun. 14 2021).

[50] World Bank, *Ghana Roads.* [Online]. Available: https://datacatalog.worldbank.org/dataset/ghana-roads-0 (accessed: Jun. 14 2021).

[51] World Bank, *Ghana Electricity Transmission Network: Africa Infrastructure Country Diagnostics (AICD).* [Online]. Available: https://datacatalog.worldbank.org/dataset/ghana-electricity-transmission-network (accessed: Jun. 14 2021).

[52] World Bank, *Ghana Rivers.* [Online]. Available: https://datacatalog.worldbank.org/dataset/ghana-rivers (accessed: Jun. 14 2021).

[53] Worldpop, "Africa Continental Population Datasets (2000 - 2020): Version 2.0 estimates of total number of people per grid square for five timepoints between 2000 and 2020 at five year intervals; national totals have been adjusted to match UN Population Division estimates for each time point(1),"

[54] L. Bauer, *Vestas V52 - 850,00 kW - Wind turbine.* [Online]. Available: https://en.wind-turbine-models.com /turbines/71-vestas-v52 (accessed: Mar. 10 2020).

[55] Global Wind Atlas, *Global Wind Atlas 3.0, a free, web-based application developed, owned and operated by the Technical University of Denmark (DTU). The Global Wind Atlas 3.0 is released in partnership with the World Bank Group, utilizing data provided by Vortex, using funding provided by the Energy Sector*

Management Assistance Program (ESMAP). For additional information: https://globalwindatlas.info" [Online]. Available: https://globalwindatlas.info/en/area/Ghana (accessed: Mar. 10 2023).

[56] Manwell, J. F. and McGowan, J. G, *Wind energy explained:: Theory, Design and Application.* [Online]. Available: https://scholar.google.com/scholar_lookup?title=Wind%20energy%20explained%3A%20theory%2C%20design%20and%20application&author=J.F.%20Manwell&publication_year=2009 (accessed: Sep. 10 2019).

[57] IRENA, "Renewable Power Generation Costs 2020," [Online]. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jun/IRENA_Power_Generation_Costs_2020.pdf

[58] H. Dagdougui, A. Ouammi, and R. Sacile, "A regional decision support system for onsite renewable hydrogen production from solar and wind energy sources," *International Journal of Hydrogen Energy*, vol. 36, no. 22, pp. 14324–14334, 2011, doi: 10.1016/j.ijhydene.2011.08.050.

[59] S. Touili, A. Alami Merrouni, A. Azouzoute, Y. El Hassouani, and A. Amrani, "A technical and economical assessment of hydrogen production potential from solar energy in Morocco," *International Journal of Hydrogen Energy*, vol. 43, no. 51, pp. 22777–22796, 2018, doi: 10.1016/j.ijhydene.2018.10.136.

[60] A. Okunlola, M. Davis, and A. Kumar, "The development of an assessment framework to determine the technical hydrogen production potential from wind and solar energy," *Renewable and Sustainable Energy Reviews*, vol. 166, p. 112610, 2022, doi: 10.1016/j.rser.2022.112610.

[61] F. Alshehri, V. G. Suárez, J. L. Rueda Torres, A. Perilla, and M. A. M. M. van der Meijden, "Modelling and evaluation of PEM hydrogen technologies for frequency ancillary services in future multi-energy sustainable power systems," *Heliyon*, vol. 5, no. 4, e01396, 2019, doi: 10.1016/j.heliyon.2019.e01396.

[62] S. Rahmouni, B. Negrou, N. Settou, J. Dominguez, and A. Gouareh, "Prospects of hydrogen production potential from renewable resources in Algeria," *International Journal of Hydrogen Energy*, vol. 42, no. 2, pp. 1383–1395, 2017, doi: 10.1016/j.ijhydene.2016.07.214.

[63] S. Raikar and S. Adamson, "Renewable energy finance in the international context," in *Renewable Energy Finance*: Elsevier, 2020, pp. 185–220.

[64] W. Short, D. J. Packey, and T. Holt, "A manual for the economic evaluation of energy efficiency and renewable energy technologies," 1995.

Appendix — Scientific publications

Paper 1:

Geospatial mapping of micro-wind energy for district electrification in Ghana[4]

[4] referenced as: A.-A. Mary, "Geospatial mapping of micro-wind energy for district electrification in Ghana," *Energy*, vol. 225, p. 120217, 2021, doi: 10.1016/j.energy.2021.120217

Energy 225 (2021) 120217

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Geospatial mapping of micro-wind energy for district electrification in Ghana

Asare-Addo Mary

Europa-Universität Flensburg, Department of Energy and Environmental Management. Munketoft 3 B, 24937, Flensburg, Germany

A R T I C L E I N F O

Article history:
Received 12 October 2020
Received in revised form
19 February 2021
Accepted 24 February 2021
Available online 27 February 2021

Keywords:
Micro-wind energy
Onshore
Resource mapping
Geospatial
Energy access
Ghana

A B S T R A C T

The present study provides an assessment of micro-wind energy potential within the 170 districts in Ghana with more focus on a distributed electricity system for district household electrification. The wind resource is assessed based on three main potentials, the theoretical, the geographical and the technical; these included an assessment of localised wind power densities, necessary environmental conditions of the terrain suitable for wind turbine installation as well as the energy generated by the turbine within the districts. The study was done using wind speed data at a hub of 50 m and then interpolated to a 1 km by 1 km grid cell to enhance granularity and localisation of the geospatial assessment of results. All input datasets were interpolated to this effect. The study is based on a single turbine model; V52/850 and used its power curve to determine the maximum energy output per grid cell. Results of the analysis are visualised using high resolution maps. Results of the analysis show that, areas along the coast and the middle belt areas show high potential with annual production more than a 2,000 $GWhy^{-1}$ per square kilometre.

1. Introduction

Access to basic energy and electricity remain a huge challenge in Sub-Saharan Africa and as such a well-known challenge facing the region [1]. This phenomenon is even more worrying as lack of energy accessibility has ripple effects on various aspects of human development such as health [2], education [3], gender parity [4,5], wellbeing, as well as life expectancy, etc. Thus, in accordance with the Paris Agreement and UN Agenda 2030 in achieving SDG 7, all member States are to ensure that electricity is made accessible to all through sustainable electricity generation means and to reduce the amount of GHG emissions in the atmosphere by decarbonising their energy systems. Member countries, of which Ghana is signatory to, were hence requested to outline and develop their nationally determined contributions (NDCs) as a roadmap in achieving their contributions to this agenda [6]. Renewable energy (RE) integration is one of such sustainable portfolios to help meet various aspects of the NDCs set targets. More significantly, RE plays a crucial role towards fostering climate resilience, reducing GHGs emissions, a poverty alleviations mechanism as well as provide an opportunity to improve and provide access to modern energy services and technology which in effect promotes energy security [7–9].

With commitment to this agenda, the government of Ghana is advised to increase the share of renewable by the year 2030 and hereinafter, the country made projections to increase the share of renewable energy by the year 2020 [10,11]. This projection and wish however, did not materialise as the country is far from meeting this commitment due to a myriad of challenges such as strong policy commitment and robust renewable energy regulatory framework and institutions that can actually enforce these policies [12], including technology to develop these RE resources. The country is thus currently faced with two major energy challenges which are, to meet the country' 2030 target which is to increase the share of renewables to decarbonise the country's energy system and the challenge of household electricity access. The country has faced serious power outages in the past years and recorded a supply deficit of about 25% in 2014 and 2015 [13]. The worst part of the present situation is that, existing power plants are unable to reach full generation capacities due to fuel supply challenges which is partly due to the unreliable and seasonal rainfall pattern coupled with the vagaries of climate change that have significantly minimized water inflow into the country's major hydroelectric generation power plant [8,14], and hence making thermal power the dominant generation power source in Ghana. Exacerbatingly, with

E-mail address: mary.asare-addo@studierende.uni-flensburg.de.

https://doi.org/10.1016/j.energy.2021.120217

Nomenclature

AWEA	American Wind Energy Association
DEM	Digital Elevation Model
EC	Energy Commission of Ghana
GHGs	Greenhouse Gases
GW h/yr	Gigawatts hour per year
GWA	Global Wind Atlas
IEC	International Electrotechnical Commission
IRENA	International Renewable Energy Agency
kW	kilowatts
ms^{-1}	Metre per second
NDCs	Nationally Determined Contributions
NREL	National Renewable Energy Laboratory
RE	Renewable Energy
SDG 7	Sustainable Development Goal 7
SWERA	Solar and Wind Energy Resource Assessment
TWh/yr	Terawatts hour per year
W/m^2	Watts per metre squared
WPD	Wind Power Density

increasing energy demand resulting from population growth, rapid urbanisation and economic growth, the country's energy system is likely to suffer additional stress [14] and this most likely will put the energy security of the country in jeopardy. There is therefore an urgent need and a clarion call on the government of Ghana to diversify the country's energy system using sustainable energy sources which are readily available in the country.

1.2. Deploying wind energy to bridge energy access gap in Ghana

In the Ministry of Energy report cited by Adaramola et al. [15], about 28% of households in Ghana do not have access to electricity. Even though the country has made significant improvements over the last 30 years (1989–2019) with access rate at 79% in 2017, many people remain unelectrified. Urban access rate as at 2017 is 90% with 65% rural penetration slightly above average. About 5 million people in Ghana still live without electricity [16,17]. This electrification deficit has become an albatross around the neck of both past and successive government with calls from civil societies, the scientific community and development organisations on government to increase access rate using sustainable means See (Fig. 1).

Another major challenge facing Ghana' energy sector is the over reliance on imported fossil fuel to power the country's power plants. A resultant of the financial challenges as a developing country being unable to sufficiently purchase diesel to power these power plants. This is also because, the country's total generation mix is predominantly thermal with a share of 69.3%, Hydro at 30.4%; and only about 0.3% from solar PV installations [10,11,18]. Other renewable energy sources like wind remain untapped.

Wind energy is however projected to be the fastest growing renewable energy resource in the global energy market, with a growing investment of 22% over the past 10 years [19]. RE is now no longer referred to as an alternative energy sources, but rather regarded as competitive energy sources [12,20]. And with increasing efforts on the part of government to promote and integrate RE in the country's energy mix, has led to the formulation of various policies and strategies towards the development of RE integration over the past years.

Ghana is however fortunate due to its geographical location, is endowed with many renewable resources such as excellent solar energy potential, mini hydro, wind potential, and biomass [21,22]. However, many of the RE projects in Ghana are focused on harnessing the potential of solar energy with limited efforts towards wind energy deployment. Wind energy deployment in Ghana is still in its infantry stages. Also, according to the Energy Commission of Ghana (EC) [23], most of the RE interventions in the country are either being carried out as pilot projects or on short term planning basis. Moreover, these pilot projects have mainly been carried out along the coastline of Ghana [15,24] even though other parts of the country have good potential worth harnessing. And as a matter of fact, the country has not produced any significant amount of wind energy over the past 30 years. According to the EC [11], as at the end of the first quarter of 2018, a construction permit was issued to start a 225 MW wind project which is a part of the pilot projects.

At the global level, several studies have been carried out to assess the potential of wind energy in many countries using different methodologies and approaches. One of the challenges of wind resource assessment is to finding and applying a more befitting approach to address the uncertainties associated with estimating the real energy output of a location [25,26]. And this re-

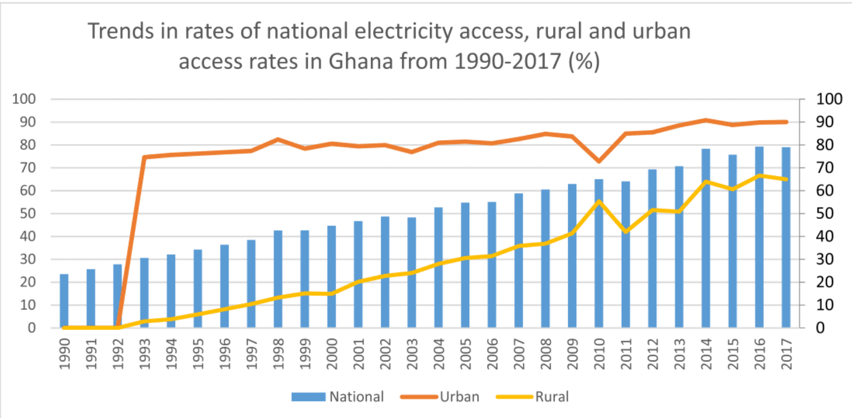


Fig. 1. Electrification Rates in Ghana from 1990 to 2017. Source: By author base on electrification rate data from the World Bank [16].

echoes one of the major barriers hindering wind deployment in Ghana as stated in the country's recent 2019 Renewable Energy Master plan [23,27]. This thus, calls for further assessment of wind energy potential to boost government and investor confidence towards wind energy deployment in Ghana. To address these uncertainties, different statistical methods have been applied in various studies to estimate wind energy potential of a wind regime. For instance, Archer and Jacobson [28] applied the Least Square method to estimate the global wind energy potential. They argued that, the Least Square technique was preferred due to the relatively few wind speed observations at 80 m hub. Mert and Karakus [29] also applied different statistical methods such as the 4-parameter Burr, 3-parameter generalized gamma, and the conventional Weibull function approaches to analyse the wind energy potential in Antakya in Turkey. They however asserted that, the Burr distribution provided a more goodness-of-fit test for representing the wind speed distribution in Antakya than the other two methods. Manwell and McGowan [30] have also stated various methods that can be used to estimate the wind energy potential of the wind regime of a location. Nonetheless, in all the statistical methods used in estimating wind potential or wind power, the most prominent are the Weibull and the Rayleigh distribution functions. However, the Weibull distribution is the most used as it has been argued to provide a good fit for determining the power in the wind distribution of a location. Adaramola et al. [15] for instance applied the Weibull probability function to examine wind power potential along the coastal areas of Ghana. Hoogwijk et al. [31] also used the Weibull distribution function to estimate the wind power potential at the global level. The Weibull distribution function has also been applied in assessing the wind energy potential in the Tirumala region in India by Kumar et al. [32]. Other scientists such as Ibrahim [33], Mentis et al. [34], as well as Manwell and McGowan [30] have also used the Weibull distribution functions to determine the wind power potential at various scales and have argued why the Weibull function is ideal especially for micro-scale analysis or at national levels.

Besides, due to the spatial characteristic of wind, wind energy assessment involves strong geospatial implications. And hence many studies now include the spatial dimension of estimating wind energy of a location by not only using these statistical methods, but also the suitability and limiting conditions of a site to reduce the uncertainties and errors in estimating the wind energy potential of a place. The application of Geospatial Information Systems (GIS) helps to identify the energy potential of a site just through visualisation of results on maps. Janke [35] applied a multi-criteria GIS approach to determine suitable land areas for wind and solar farms in Colorado. He further ascribed the GIS environment as a tool capable of combining multiple unrelated criteria in a meaningful manner. This thereby being able to quantify the energy output, the geographical conditions of a place suitable for turbine installation, as well as help to examine the social acceptability of wind farm project in an area to produce a more realistic energy output result in situ. Baffoe and Sarpong [36] also applied similar geospatial multi-criteria method to perform a site suitability assessment to identify locations in Ghana that are geographically and socially suitable for wind farm development. Mentis et al. [34] also used GIS to estimate and show the wind energy potential of countries in Africa. Their paper included an assessment of the wake effect of turbine as well as the amount of energy that can be generated considering grid restrictions and without grid restrictions. Results of their analysis showed that, about 82.8 TWh/yr of wind energy can be generated in Ghana with or without grid restrictions. In a report published by IRENA [37] on the other hand, estimated about 600 TW/yr of technical potential for all areas with turbine capacity factor greater than 20% in Ghana.

Further, with efforts to increase the share of RE in Ghana, in 2002, the government introduced the Solar and Wind Energy Resource Assessment (SWERA) initiative to explore the potential of solar and wind energy in the country [18,23]. The SWERA initiative was one of the earliest efforts by government which included partnership with the National Renewable Energy Laboratory (NREL) to carry out wind speed measurements and to estimate the wind energy potential in some areas along the coast. Their assessment showed that, over 300 MW installed capacity could be generated which could generate over 500 GWh to augment the country's energy supply [18]. However, the SWERA was mainly a theoretical assessment as it did not consider an assessment of certain geographical restrictions such as land-use features, accessibility and proximity to grid infrastructure, etc. as stated in the SWERA report [24,36] as this could have had impact in the estimation of the wind energy generated.

In addition, following the SWERA initiative, there has been some but limited research to provide further assessment on the viability of wind energy deployment in Ghana. A review of current literature on wind energy development in Ghana, show a trend that seem to put more emphasis on developing huge wind farm to feed into the national electrical grid with no or limited attention to access in off-grid areas that have very high wind energy potential to supply electricity to people in these off-grid areas. Current research include Asumadu-Sarkodie et al. [38] who carried out an assessment of the technical and economic potential of wind energy in Ghana but unlike this present study, their assessment focused only on 11 selected locations mainly along the coastline of Ghana. Their assessment was also seemingly geared towards assessing the potential of wind energy mainly for grid connection rather than a comprehensive potential assessment of all onshore areas of Ghana and special attention to generation in off-grid areas that can benefit from the high wind energy potential in these areas. Their assessment also did not consider the geographical constraints associated with wind turbine installations. These and among others are what the focus of the present study seeks to heighten and contribute towards universal energy access through distributed energy systems. Same can be said of the wind energy assessment in Ghana by Adaramola et al. [15]; their assessment also focused on some selected areas along the coastal areas rather than the entire country. Again, their assessment did not consider the geographical conditions of Ghana terrain that must be considered to ensure optimal operation of the selected wind turbine. Essandoh et al. [39] also carried out wind potential in Ghana using the RETScreen and HOMER software to identify areas with good potential in Ghana. Their paper also placed emphasis on a grid connected system. The present research however applied a different approach and methodology, using the GIS software to visualize and estimate the wind energy potential as detailed as at the district level. Also, in this study, the Weibull distribution function was used to compute the power densities as well as calculating and using the real air densities of these locations.

Thus, from all the assessment of wind energy potential, one can conclude that, depending on the objective of the RE assessment, the wind energy generated could differ due to different considerable factors such as type of turbine used, the statistical method used, and geographical factors, etc, as well as either as a huge commercial wind farm or as micro project for a distributed system. As reiterated in the 2014 IRENA report [37], it is crucial to be transparent about assumptions upon which the wind assessment is being carried out in order to help compare the real values with on-site realities. This study hence provides an assessment of not only the technical and theoretical potential, but also the geographical restrictions of Ghana' terrain (onshore) in assessing and mapping the wind energy potential in all the districts in Ghana.

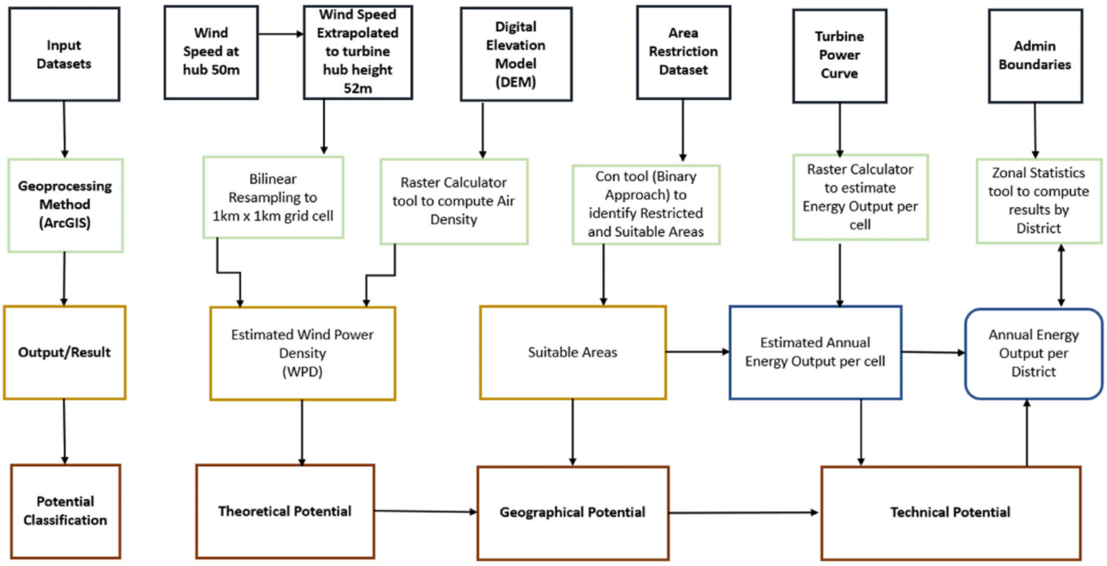


Fig. 2. Methodology concept.

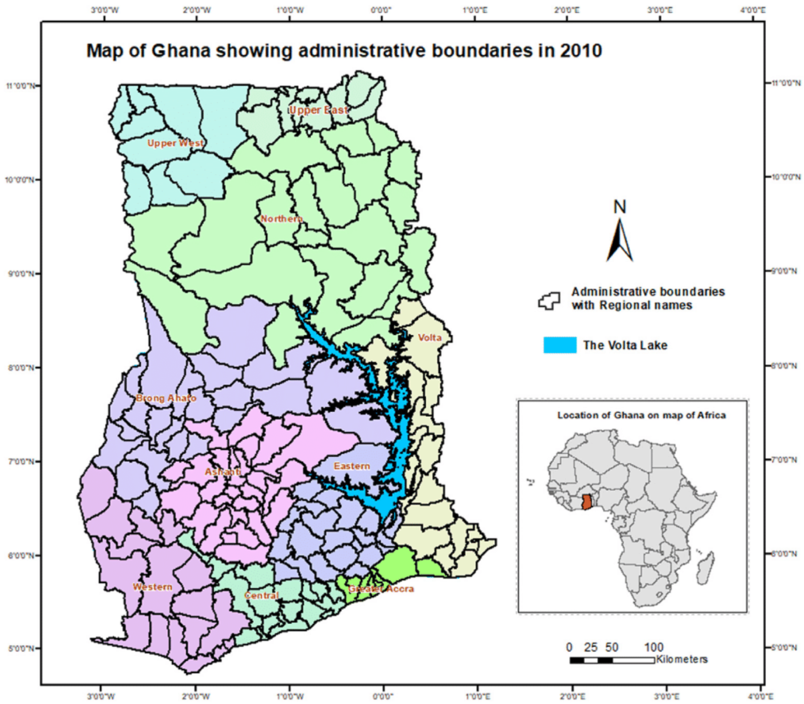


Fig. 3. Administrative Map of Ghana in the year 2010. Source: By Author.

Table 1
Categories of wind energy potential.

Category	Definition
Theoretical potential	The total global energy content of the wind (kWh year $^{-1}$).
Geographical potential	The total global amount of land area available for wind turbine installation taking geographical constraints into account (km^2).
Technical potential	The wind power generated at the geographical potential including energy losses due to the power density of the wind turbines and the process of generating electricity using wind turbines (kWh year $^{-1}$).
Economic potential	The technical potential that can be realised economically given the cost of alternative energy sources (kWh year $^{-1}$).
Implementation potential	The amount of economic potential that can be implemented within a certain timeframe, taking (institutional) constraints and incentives into account (kWh year $^{-1}$)

1.3. Aim of study

The overarching aim of this study is to quantify and estimate the amount of onshore wind energy that can be generated per km^2 at the district level to meet the unmet electricity demands within the districts. To achieve this aim, the below objectives have been assessed:

i. To estimate the theoretical wind power potential in Ghana.
ii. To estimate the geographical wind power potential per administrative district in Ghana.
iii. To estimate the machine power/technical wind energy potential per administrative district in Ghana.

The above three main potential assessments were used to estimate the wind energy available per each district within the regional boundaries. The present study tries and provides a maiden effort towards a geospatial disaggregated assessment of wind energy potential in Ghana, i.e. at the district level.

The outcome of this study is shown using high-resolution maps at microscale level and by using the actual localised data in Ghana to estimate the actual energy output (e.g. actual air density values per district were calculated and used). The mapping was done at a granular level due to the extensive level of detail which involved dividing the individual district land areas (i.e. Admin 2 level [40]) into 1 km × 1 km grid cell size.

2. Methodology

This chapter gives a chronological assessment of how the objective of this study was achieved. The result of this assessment is expected to provide wind energy as a viable sustainable energy transition option available to the Ghana government towards decarbonization of the county's energy system as well as towards sustainable universal energy access. This study is particularly relevant towards universal access as even 1 kW of electricity can move a household to an upper or higher Tier level under the assumptions of the Multi-Tier-Framework [41,42].

To achieve the aim of the study, a multi-criteria geospatial method was used to assess the viability of wind energy development in all 170 administrative districts in Ghana using the base year 2010 [43]. The year 2010 was used as a reference year because it is the latest year that has all the available information needed for district analysis especially regarding population statistics as well as regional and district administrative boundaries.

The geospatial approach is based on a grid cell analysis to quantify the annual wind energy output per cell (i.e. GWh/y). Also, it is important to mentioned that, the focus of this study is not to develop a huge commercial wind farm but rather a small-scale wind distributed power system where there is wind potential and the location of the turbine siting is relative to the end-user and the electricity distribution system, and thus as stated earlier, an increase in even watts of electricity is of essence towards universal electricity access.

Aside, the multi-criteria aspect of this study involves an assessment of certain key characteristics and conditions of Ghana' topography necessary for wind power generation. For the technical assessment, the wind turbine power curve was used. The chosen wind turbine for the analysis is VESTAS V52/850. The selection of a suitable turbine for a site is among others mainly dependent on the wind speed regime, as well as the quality and the capacity of the electric transmission network. Due to the nominal onshore wind regime of Ghana, it is technically and economically viable to select micro turbines that suits the Ghana grid [44]. More especially because the focus of this study is to develop micro-wind energy to augment household electrification within districts in Ghana. In addition, the intermittent flow of wind power creates problems to the power grid as a result of the power fluctuations that degrades the quality of grid infrastructure [34], this situation is even worse for countries with weak grid infrastructure [30,44]. VESTAS V52/850 turbine operates at wind speed as low as 3 ms^{-1} and a cut-off wind speed[1] at 20 ms^{-1} [45]. It also has operational wind speed requirements that is suitable for the onshore wind speed regime of Ghana which ranges from 1.0 ms^{-1} ≈ 9.7 ms^{-1} at 50 m hub height. This turbine is mainly suitable for onshore wind energy generation [45].

The wind speed data used for this study was obtained from the Global Wind Atlas portal (GWA) at a hub height of 50 m as.tiff in GIS raster format [46].The 50 m hub height climate data forms part of the GWA version 3 datasets that were modelled over a simulation period from 2008 to 2017 [46]. According to the GWA report, during modelling of the wind data, some resulted in either being truncated (e.g. CFSR, ERA-Interim) or interpolated (e.g. CFDDA) and thus the data is not in its native model grid cell (e.g. no information on real surface elevation and land use) and as a result there are implications for the generalized approach used [46]. The GWA model thus applied a generalized approach to resample the wind speed distribution based on different terrain characteristics. Some datasets were downscaled to 0.1 km, 1 km, 20 km, etc. depending on the terrain or topography where the wind climate datasets were collected. Hence, to achieve a more localised and micro-scale analysis, the 50 m hub wind speed data as well as other climate data were resampled to a 1 km × 1 km grid cell with the administrative boundaries of Ghana in focus. Grid cell as used in this study refers to 1 km^2 of land area. Fig. 2 below provides a conceptual flow-chart of the methodology process. Aside the challenge of acquiring raw and ground data for this study, the major limitation of this research is that, exact replication of all the models and algorithms will require the use of commercial ArcGIS software and more importantly the advanced licensed environment to access certain tools needed to carry out this assessment.

[1] For more information on various wind shear models, check [30].

Table 2
Classification of wind power density at 50 m.

Wind Power Density Class	Wind Speed (m/s)	Wind Power Density (W/m^2)
1	0–5.6	0–200
2	5.6–6.4	200–300
3	6.4–7.0	300–400
4	7.0–7.5	400–500
5	7.5–8.0	500–600
6	8.0–8.8	600–800
7	8.8–11.9	800–2000

2.1. Description of the study area

Ghana is in West Africa on Latitude 7.9465° N and Longitude 1.0232° W, which is few degrees north of the Equator and along the Gulf of Guinea. The terrain mainly consists of small deserts in the northern part with few scattered hills and highlands like the Gambaga Escarpment with plains and highlands in the southern part. The mountains and ranges cut across the middle belt area; central-south to the further eastern part of the country, i.e. the Akwapim-Togo Ranges which include the Kwahu Plateau and Mt. Afadjato. Mt. Afadjato is the highest point in Ghana of ~885 m high above sea level [47]. About half of the country lies less than 153 m above sea level.

As stated, the referenced year statistics data used to carry out analysis for the study is 2010. This was due to the challenge of acquiring census data with corresponding administrative boundaries for any recent changes over the years. In the year 2010, there were 170 districts and 10 Regional administrative boundaries in Ghana [48] with an average national household size of 4.4 [43]. Total population was around 21million people (Fig. 3).

2.2. Categories of wind energy assessment

There are different categories of assessing the potential of wind energy depending on the objective and the focus of the study. Van Wijk and Coelingh [49] outlined four categories of wind energy potential. The study focuses only on the first three potential categories and at a disaggregate level (e.g. X value per grid cell per zone or per polygon area) (Table 1).

2.3. Interpolation: adjustment of the wind speed distribution

The wind speed data downloaded from the GWA as well as all the input raster datasets were readjusted to a higher grid cell resolution to a 1 km × 1 km grid cell to achieve some level of granularity in estimating the WPD per grid cell of the district land area. The interpolation analysis was done in order to show a seemingly granular detail of the terrain and to also achieve same cell size for all the input datasets used in the analysis of this study.

The bilinear interpolation technique was used to resample the wind speed distribution to a 1 km by 1 km grid. With bilinear interpolation, the cell value is determined based on a weighted distance average of the four nearest input cell centres [46,50] and more ideal for continuous data like wind speed distribution.

2.4. Hub height extrapolation

The speed of wind (U) changes with reference to changes in height, altitude or elevation due to the frictional effects at the surface of the terrain which is characterised by vertical wind shear. Due to the wind shear anomalies, it is important to extrapolate the wind speed height to the hub height of the chosen wind turbine (i.e. 52 m) [45]. The wind speed data used is the average annual wind speed at a hub of 50 m. Many scientists have proposed different models to estimate the wind shear exponent (α) and the corresponding heights[2]. For many, assuming the terrain is flat, homogenous, and a neutral stratification of the atmosphere, a good vertical wind shear can be estimated either by the log law or the power law. The power law model is given as [30]:

$$U_2 = U_1 * \left(Z_2/Z_1\right)^{\alpha} \tag{1}$$

where U_1 = Velocity at height Z_1; U_2 = Velocity at height Z_2; Z_1 = Height 1 (lower height); Z_2 = Height 2 (upper height); α = wind shear exponent.

The wind shear exponent can be expressed as a function of the wind speed and the wind speed hub as proposed by Justus (1978) [51]:

$$\alpha = \frac{0.37 - 0.088 \ln\left(U_{ref}\right)}{1 - 0.088 \ln\left(Z_{ref}/10\right)} \tag{2}$$

where U is given in m/s and z_{ref} in m.

2.5. Theoretical potential of wind

The theoretical energy power for this study estimates the potential of Ghana' wind energy potential at the global level computing only WPD. Calculating wind power at the grid cell level is conceptually difficult [31], thus energy intensity derived from solar irradiance was used. The kinetic energy from the wind contains mass of air and the mass also contains speed which is referred to as Wind Power Density (WPD). The WPD formula is given as:

$$WPD = 1/2AU^3 \tag{3}$$

where WPD (Wm^{-2}) is the power per m^2 of the swept area (A) of selected turbine, ρ is the air density in (kgm^{-3}), and U is the wind speed per grid cell ($m\ s^{-1}$).

Caution must however be taken that, equation (3) is under the tacit assumption that the wind blew with a velocity of U all the time. Therefore a more accurate estimate for WPD will include summation of all the wind speed data taken over time as below [52]:

$$\mathbf{WPD} = 1/2 * 1/n * \sum_{j-i}^{n} \left(\rho_j * U_j^3\right) \tag{4}$$

where n is the number of wind speed observations and ρ_j and U_j are the j^{th} (1^{st}, 2^{nd}, 3^{rd}, …etc.) observations of the air density and wind speed per respective site.

2.5.1. Air density estimation

Since air density and speed changes with every reading, a more accurate result will consider every data interval [34,52–54]. The air density is inversely proportional to temperature and elevation; an increase in elevation and temperature will cause a decrease in air

[2] The ideal gas law has been used to estimate the air density for local area per site. It could also be expressed as a function of temperature and pressure [54]: $\rho = P/_{R*T}$; where ρ is the air density, P is the absolute pressure; and R is the specific gas for dry air, which is equivalent to 287.058 $J/(kg\ K)$, and T is the local temperature in K. [54,55].

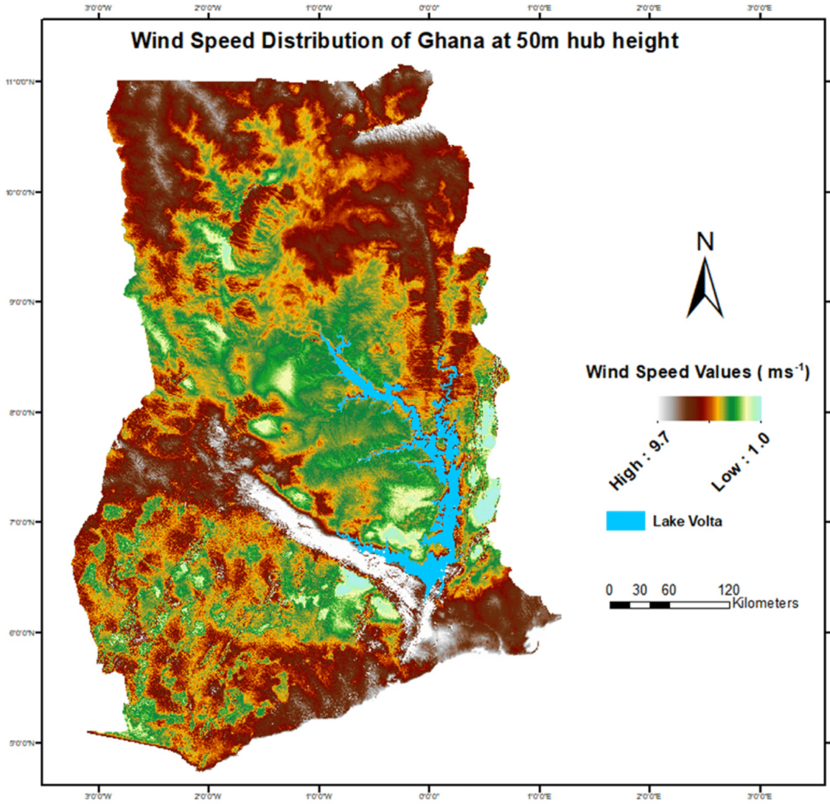


Fig. 4. Wind Speed distribution in Ghana at a 50 m hub.

density. For this study, air density (ρ) is not equal to 1.225 kg/m^3 (standard air density value) as used in many studies but rather consideration is given to the temperature variations which provides a more accurate estimation of the WPD is preferred using the ideal gas law formula[3] where the location' elevation above sea level was used to estimate the air density per cell. The formula is given as [30]:

$$\rho = 1.225 - \left(1.194*10^{-4}\right)*z \tag{5}$$

where z is the location's elevation above sea level in meters.

The formula used here is an assumption of how wind speeds are distributed in a Rayleigh wind speed frequency curve, and it is given as [30,56];

$$\mathbf{WPD} = 0.955*\rho*U^3 \tag{6}$$

where K = 1.91 is the value determined by the shape of the Rayleigh distribution pattern that the wind speeds follow. Result or output of the estimated actual air densities per district for this study has been compiled into a GeoTIFF file and openly accessible at [57].

This method was used to estimate the theoretical WPD per cell for all the 170 districts in Ghana as shown in Table 2 as well as to estimate the theoretical WPD classification for wind speed ranges. The wind speed class ranges from Class 1 for winds with least energy to Class 7 for winds with the most energy. The classification is based on the methodology stated in the W. Cliff report. The WPD estimations below are based on the wind speed classification at hub 50 m based on NREL wind speed classification and under assumption[4] stated in the report [30,56,58] (Table 2).

2.6. Geographical potential

Geographical potential of wind simply is the total amount of an area (km^2) of land at a specific location available and suitable for siting a wind turbine holding geographical constraints constant. This research is restricted to onshore terrain. The characteristics of the terrain was grouped into two categories to assess the suitability of the terrain for siting a turbine per cell. It is important to stress that, in this study, priority or level of importance were not assigned to variables. The Boolean approach was used to factorise restricted areas and suitable areas (0, 1), where Boolean value 0 represent areas that are restricted due to the selected restriction criteria and

[3] a) Vertical extrapolation of wind speed based on the 1/7 power law.b) Mean wind speed is based on Rayleigh speed distribution of equivalent mean wind power density. Wind speed is for standard sea-level conditions.

[4] Power curve of a wind turbine is the electric output (kW) of the turbine at different wind speed levels (ms^{-1}).

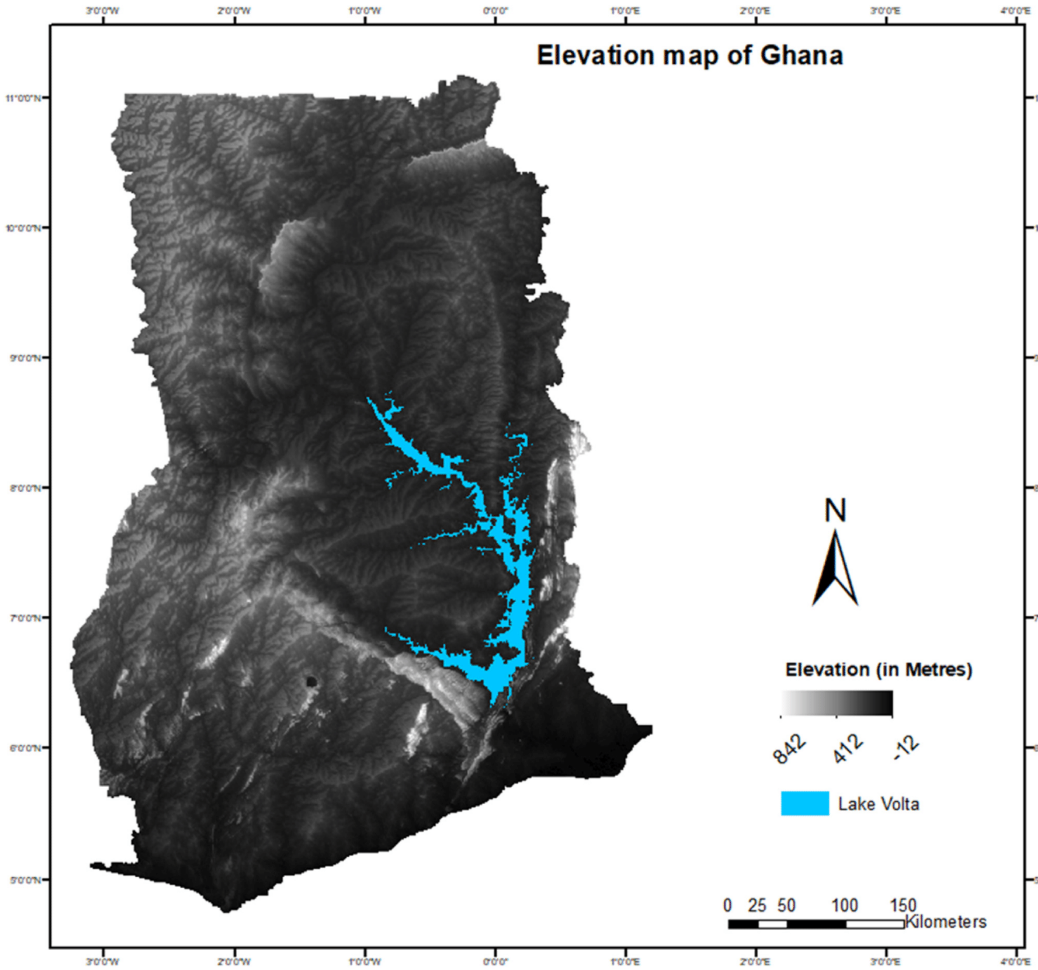


Fig. 5. Digital elevation model (DEM) of Ghana.

Boolean value 1 represent suitable land areas suitable for wind turbine siting. The geographical potential equation was adopted from [59] and it is given as:

2.6.1. Geographical potential equation

$$S = \sum_{i=1}^{x} w_i C_i \prod_{j=0}^{y} R_j \quad (7)$$

where S is the Suitability for siting a wind turbine; w_i is the Boolean weight for suitability criteria; C_i is the suitability criteria; and R_j is the restriction criteria.

2.6.1.1. Suitability criteria. In this study, the basic necessary conditions of the terrain for wind energy development have been examined. The topography or the terrain of a location plays an integral role in siting a wind turbine because wind energy penetration and development involve strong spatial implications. The study performed a simulation analysis on the Digital Elevation Model (DEM) of Ghana to determine basic characteristics of the terrain to consider before siting a wind turbine such as elevation, wind speed hub, slope, roughness, etc. The terrain should have certain minimum characteristics to enable the installation and performance of the turbine which is dependent on the DEM of terrain. These features and characteristics included:

2.6.1.1.1. Wind speed. Wind speed is one of the major factors to consider in the development of a wind farm or wind turbine installation. The 50 m wind speed data used was downloaded from the GWA portal [46] on a mesoscale level. The wind speed distribution was interpolated to a considerable granular level of a 1 km × 1 km grid. At a hub of 50 m, the average annual wind speed

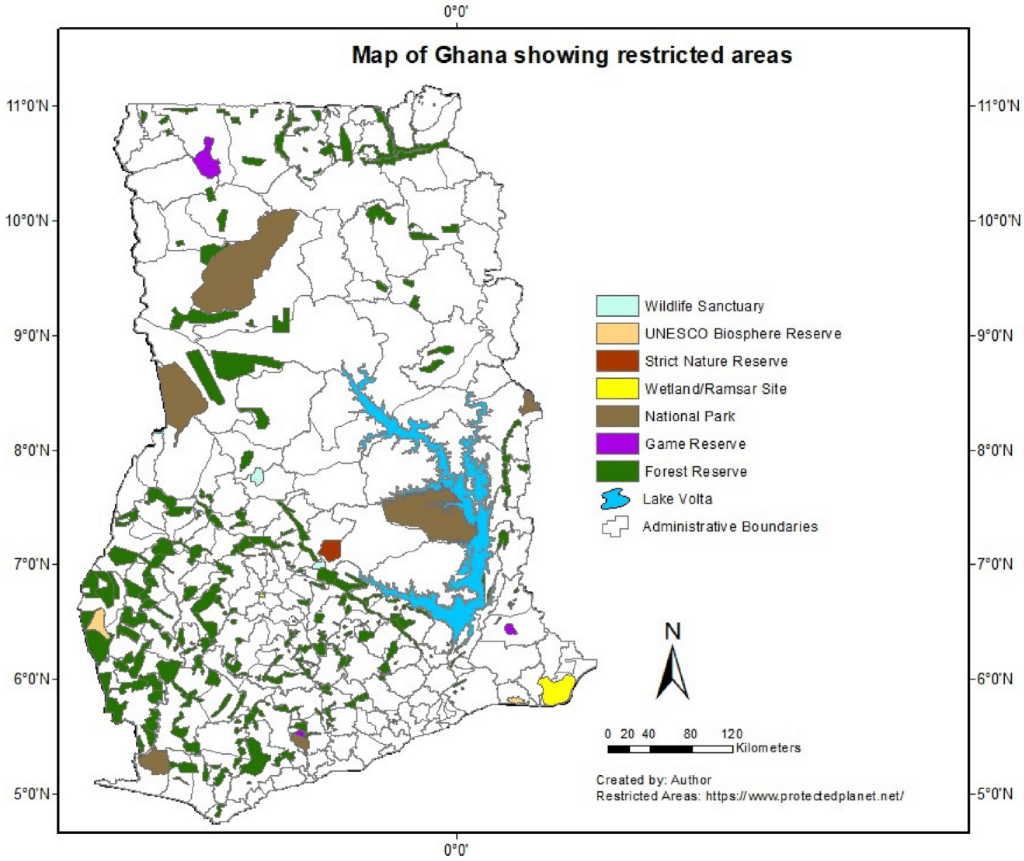


Fig. 6. Map of Ghana showing restricted areas.

ranges between 1.0 ms^{-1} to 9.7 ms^{-1}. Wind turbines that are built today have power curves[5] that can be programmed to suit any wind speed class [31]. It has also been argued that, about 80% of global land areas has annual average wind speed lower than 4 ms^{-1} at 50 m hub and if estimates are confined to a cut-in[6] wind speed of 5 ms^{-1}, areas such as Sub-Saharan Africa and the total Indian continent will be cut off [31]. For this study, Vestas V52/850 wind turbine was used because of its operational wind speed requirements. The wind turbine operates at wind speed as low as 3 ms^{-1} and a cut-off wind speed[7] at 20 ms^{-1}.

Thus, based on the turbine cut-in wind speed, a geospatial vectorisation or weighting was performed to select wind class from 3 ms^{-1} and above (wind speed > = 3 ms^{-1}) (Fig. 4).

2.6.1.1.2. Elevation of the terrain. Elevation or slope of the terrain is very important when estimating the distribution of wind speed of location. The steepness or gentleness of the topography can affect the stability of the turbine. Higher elevation is known to increase wind turbulence that could destroy the turbine. Steeper ground also reduces accessibility in transporting the turbine resulting in increased building cost [60]. Some researchers have estimated maximum slope threshold from 10% [61] to 30% [62]. Hoogwijk [31] proposed a suitable area at an altitude below 2000 m for siting turbine. By this, the entire topography of Ghana is quite suitable for siting turbine as it falls within a range of −12 m to 842 m above sea level by the DEM data used [63]. A 30 arc-second DEM data of Africa [63] was used and resampled to a 1 km × 1 km grid cell. The DEM data downloaded from ESRI was for the entire globe so, the extract by mask tool in ArcGIS was used to extract the geographic boundaries and extent of Ghana for the analysis and resampled. By this, Akwapim-Togo Ranges including Mt. Afadjato (~885 m) which is the highest point in Ghana are suitable for siting wind turbine. It must be stated that, from the DEM dataset used, the highest point in Ghana is 842 m above sea level (Fig. 5).

2.6.1.2. Restriction criteria. These are unfavourable areas of the terrain that are not suitable for turbine installation. It must be mentioned however that, these restrictive criteria are indicative

[5] Wind speed cut-in is the point at which the turbine starts producing electricity from turning.

[6] Wind speed cut-off is the maximum wind speed at which the turbine gets so fast and stands the risk of damage from operating further.

[7] It can also be defined as the ratio of the full-load hours and the total amount of hours in a year [31].

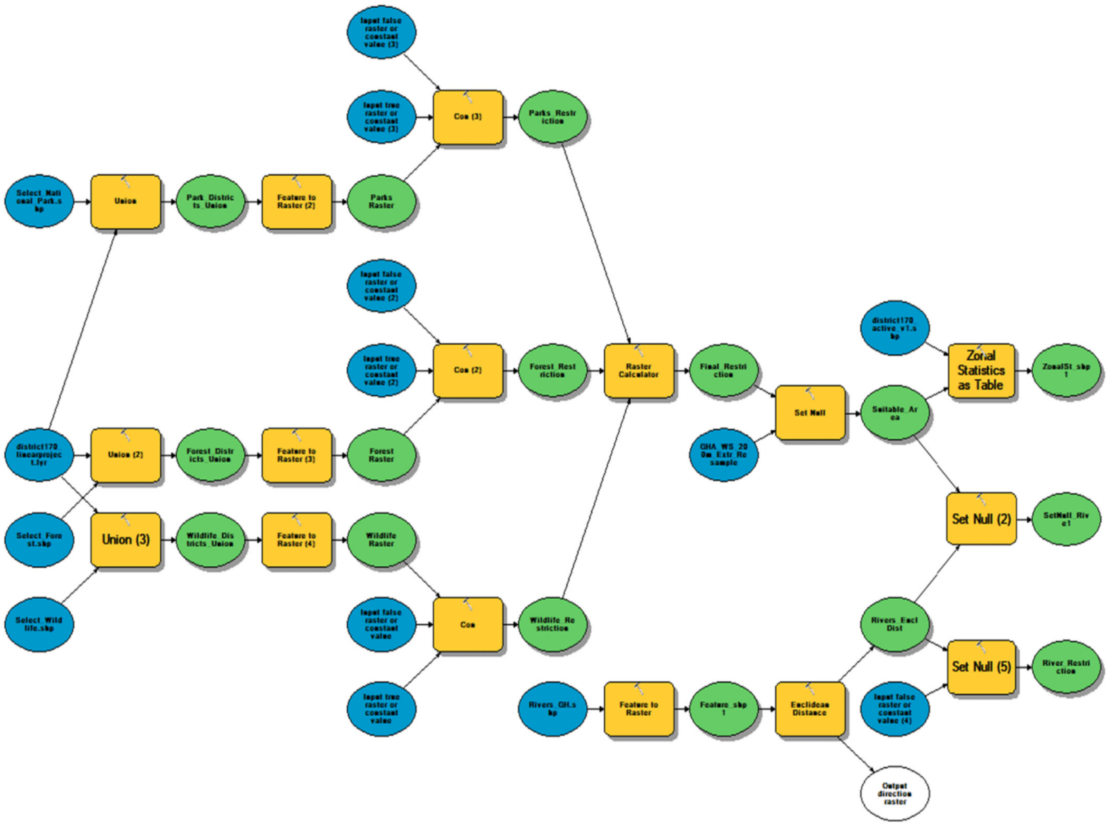


Fig. 7. Geospatial suitability and restriction model.

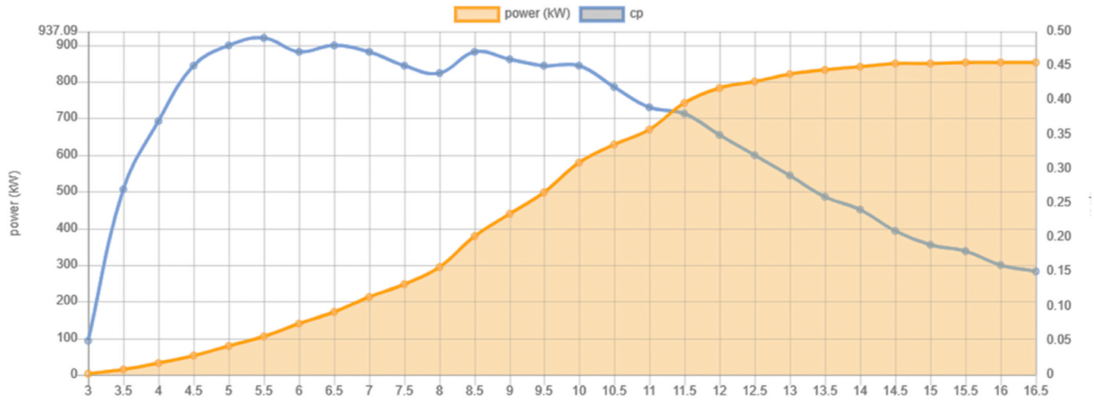


Fig. 8. Power curve: VESTAS V52/850 [45].

and may differ depending on the objective of the researcher and local land-use regulations and laws in the study area. This is because other researchers have considered other constraining factors such as social acceptability of wind farm project [64]; like level of noise of the turbine, proximity to critical infrastructure, etc. But for the purpose of this study, the focus is mainly on

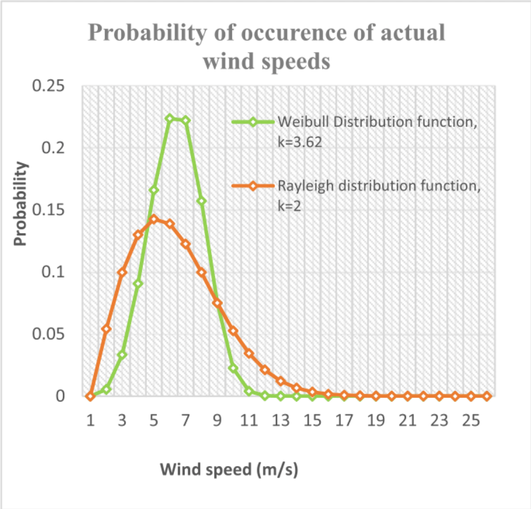


Fig. 9. Variations in probability of occurrence between Weibull and Rayleigh density function.

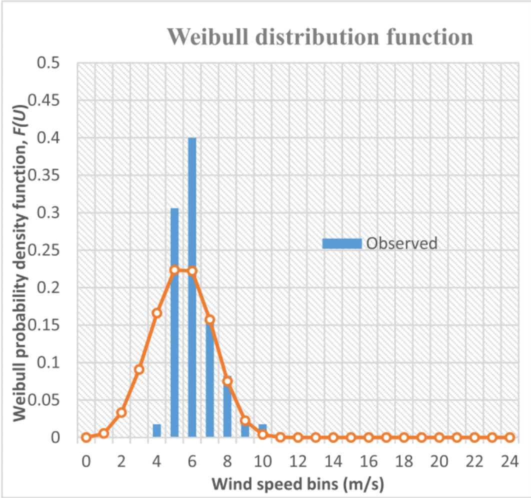


Fig. 10. Estimated Best-fit Weibull for the wind speed distribution.

environmental/climatic constraints. These excluding areas are mainly protected land areas like the Volta lake, national parks, forest reserves, wildlife reserves, and wetlands, etc., which were retrieved from the World Database on Protected Areas [65,66]. All restriction criteria were completely excluded from the analysis. Road and grid network were also not considered in this analysis as these are some necessary conditions that must nonetheless be considered by stakeholders to invest in energy infrastructure to boost electricity access to achieve universal access by all (Figs. 6 and 7).

2.7. Technical assessment of wind power in Ghana

Here, the wind energy generated at the geographical potential including mechanical losses of the wind turbines and the process of generating electricity using wind turbines (kWh year^{-1}) were calculated. This is primarily based on the wind energy that the specified turbine can generate given the level of suitability of the location as well as the geographic suitability over a number of hours in a full year. Calculating the technical potential of local winds is complex as characteristics differ considerably from one location to another. Hence, calculations were based on approximations.

2.7.1. Statistical analysis of wind data: probability distribution

Probability distribution methods were used to determine the potential of a site and to estimate the amount of wind energy output that can be generated from a particular wind turbine installed there [51,67,68]. Two probability distribution equations are mostly used to estimate the wind regime: the Weibull or the Rayleigh distribution. The difference between the two is, the latter uses the mean wind speed value while the former uses both the mean and standard deviation values of the wind regime. The study utilizes the Weibull distribution to estimate the wind speed distribution, which relies on two parameters: the shape factor k and the scale factor c, which are both functions of $\overline{U}$and σU [25,30,51]. The Weibull probability density function is given below, where U is the wind speed:

$$P(U) = {}^{k}\!/_{c} * \left({}^{U}\!/_{c}\right)^{k-1} \exp\left(-\left({}^{U}\!/_{c}\right)^{k}\right) \tag{8}$$

$$F(U) = 1 - \exp\left[-\left(\frac{U}{C}\right)^{k}\right] \tag{9}$$

The mean wind speed value $\overline{U}$, and the value of k and c are estimated by the following steps:

$$\overline{U} = c\Gamma\left(1 + {}^{1}\!/_{k}\right) \tag{10}$$

$k = \left({}^{\sigma U}\!/_{\overline{U}}\right)^{-1.086}$ where σU represents the standard deviation of the wind speeds averages and k is $1 \le k < 10$ [51].

The value of c can be solved by substituting equation (10) into equation (11). This method still requires a gamma function:

$$c = \frac{\overline{U}}{\Gamma\left(1 + {}^{1}\!/_{k}\right)} \tag{11}$$

The Rayleigh probability density function is given as [30,51,56];

$$P(U) = \frac{\pi}{\overline{U}}\left({}^{U}\!/_{\overline{U}^2}\right) exp\left[-\frac{\pi}{4}\left({}^{U}\!/_{\overline{U}}\right)^{2}\right] \tag{12}$$

$$F(U) = 1 - exp\left[-\frac{\pi}{4}\left({}^{U}\!/_{\overline{U}}\right)^{2}\right] \tag{13}$$

2.7.2. Wind turbine energy production: machine power output

This refers to the amount of wind energy that a turbine can produce at a given site with available wind speed data. The power available from a wind turbine can be estimated using machine

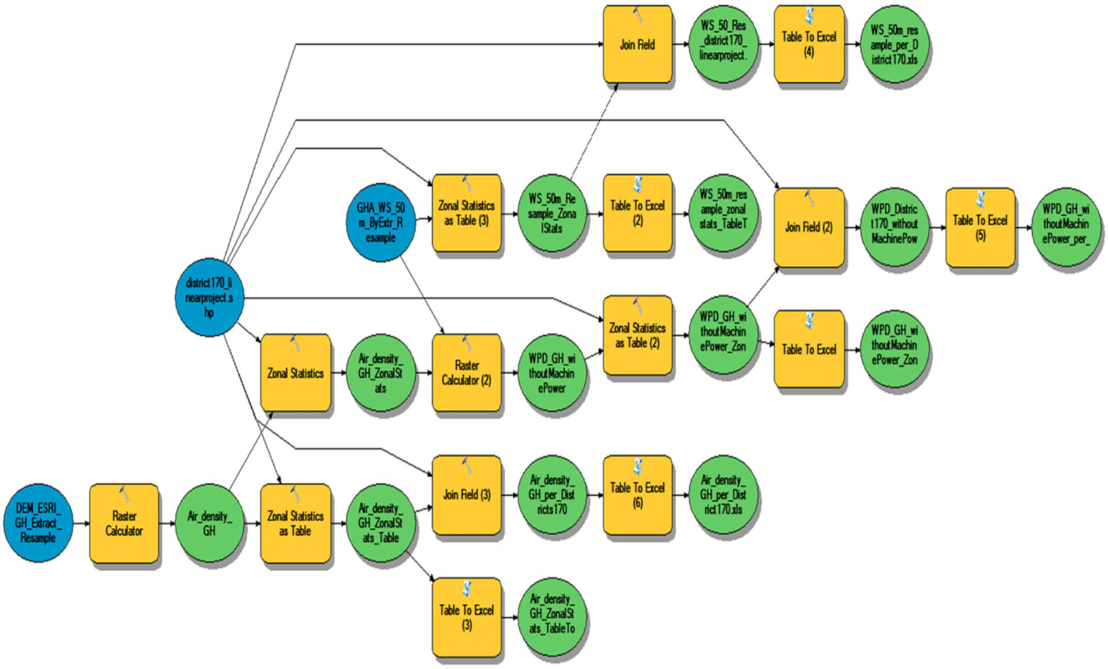


Fig. 11. Estimation of theoretical WPD and Air densities per District Model.

power curve of the turbine. As mentioned earlier, the turbine used for this assessment is Vestas V52/850 kW (swept area: 2124.0 m^2 and rotor diameter: 52 m) [45].

Machine power curves are usually based on tested data as stated in IEC (2005) [69] or AWEA (1988). The machine power curve shows three main characteristics of wind speeds, namely [30,31];

- Cut-in wind speed: minimum wind speed for power generation.
- Rated wind speed: wind speed with output at rated power.
- Cut-off wind speed: maximum wind speed until the generator is turned off (Fig. 8).

For a given wind regime and the probability density function, $p(U)$, and a known turbine power curve,$P_w(U)$, the average wind turbine power, $\overline{P}_w$, is given as [30]:

$$\overline{P}_w = \int_0^\infty P_w(U)p(U)dU \quad (14)$$

$$\overline{P}_w = \left(\int_0^\infty P_w(U)p(U)dU \right)(t) \quad (15)$$

The average wind turbine power was then used to estimate the capacity factor; CF[8]. The capacity factor of a wind turbine at a given site is the ratio of the actual average energy output of the turbine to the energy that could have been produced if the turbine ran at its rated power, P_R, over a period of time (t); where time period is the number of hours(h) in a full year, i.e. 8760 h/year. It must be mentioned that, the value of $\overline{P}_w$(actual power available) is highly influenced by the nature of the wind distribution on site. Hence:

$$CF = \overline{P}_w \Big/ P_R \quad (16)$$

The turbine power curve can also be determined by the power available in the wind and the rotor power coefficient, C_p. $P_w(U)$ can thus be expressed as [30]:

$$\mathrm{P_w(U)} = 1 \Big/ 2\mathrm{AC_pU^3} \quad (17)$$

where C_p is the maximum power coefficient; and the dimensionless theoretical maximum value of 0.59 that was used for the estimation and A = rotor swept area, (m^2) ≈ π D^2/4 (D is the rotor diameter in m, π = 3.1416) [30].

The Weibull distribution can thus also be possibly rewritten as a function of the average wind power using a cumulative distribution function as:

$$\overline{\mathrm{P}}_\mathrm{w} = \int_0^\infty \mathrm{P_w(U)dF(U)} \quad (18)$$

The figures below show variations in frequency of occurrence of the wind speed data used between the Weibull and the Rayleigh density functions as well as an estimated best fit shape factor value (k) which is equal to 3.62. The analysis shows a higher probability of occurrence using the Weibull compared to the Rayleigh

[8] Wind speed cut-off is also the maximum wind speed at which the turbine gets so fast and stands the risk of damage from operating further.

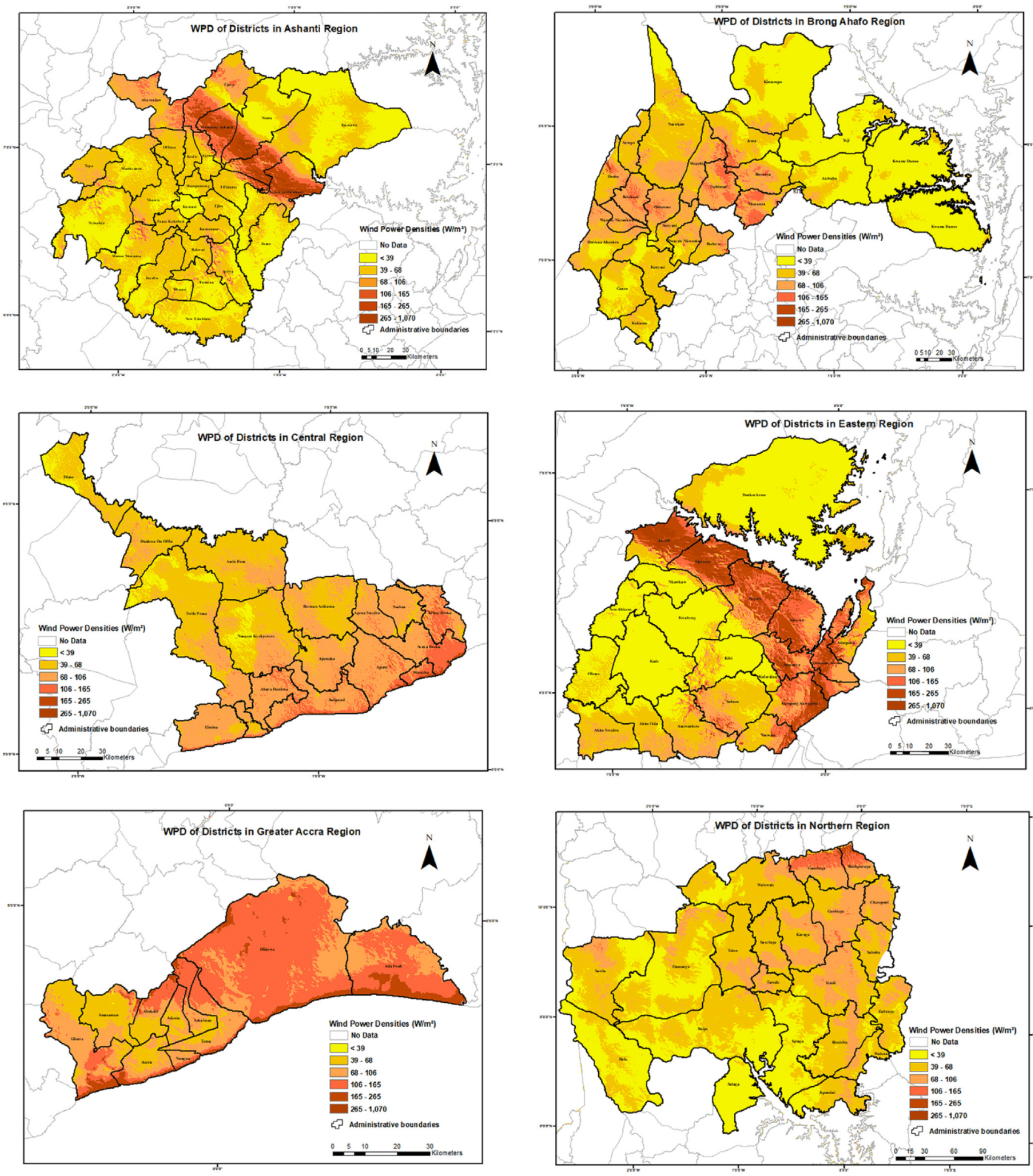


Fig. 12. Theoretical Wind Power Density maps of Districts within the 10 Regional Boundaries of Ghana.

distribution. This justifies why the Weibull function is preferred and a best fit for the wind speed distribution in Ghana (Figs. 9 and 10).

3. Results

The results are based on the outcome of the calculations and estimations used to compute the energy output per cell in Ghana at

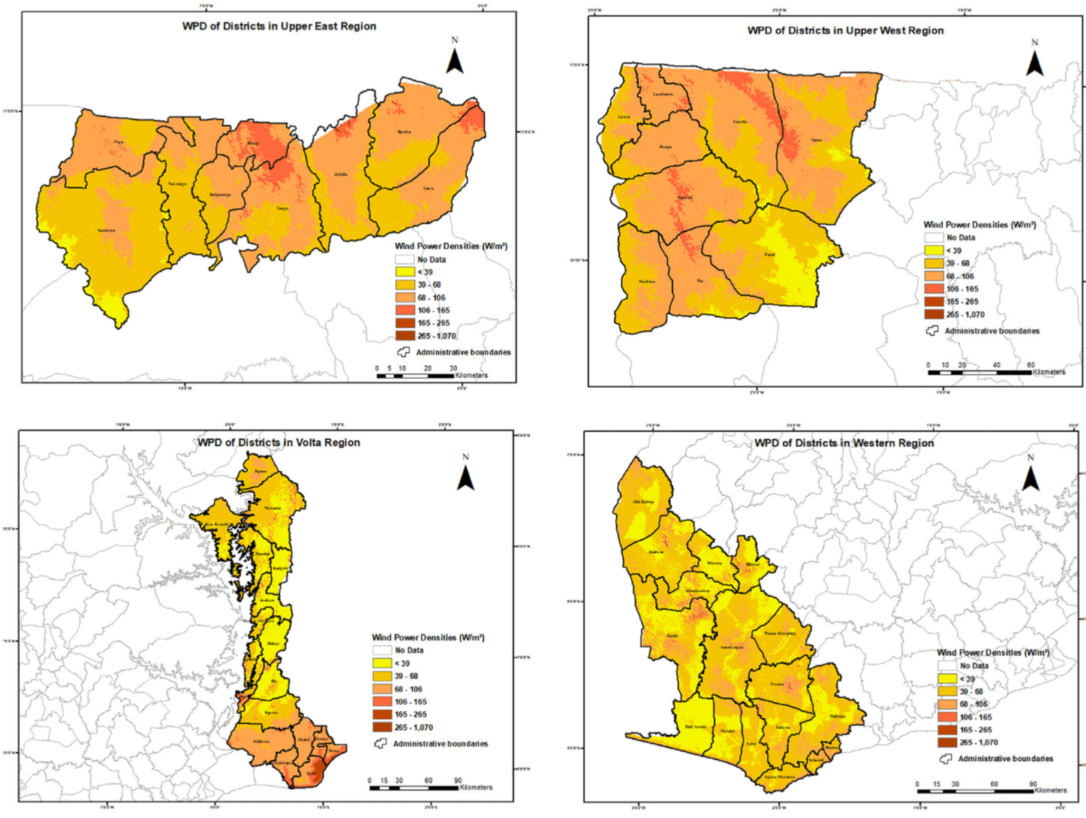


Fig. 12. (*continued*).

the district level. The maximum values of a parameter (e.g. wind speed, air density, etc.) of grid cells per district were used to estimate the results of the energy potentials. The results of the three wind energy potentials are also explained.

3.1. Theoretical potential assessment

This involves an assessment of the total wind power that could be produced without any restriction criteria; and by estimating the WPD at the 170 districts level as well as the general assessment at the national level. The theoretical model was created in ArcGIS, using the raster calculator tool to compute WPD maps per grid cell. Also, since it is a bit challenging to directly see the values per cell by looking at the maps, the zonal statistics as table tool was used to populate the values per districts within the 10 regions. Here, the actual air density and wind speed per district were used to compute the WPD at the 170 district levels. At the national level, Ghana has total theoretical onshore WPD of approx. 0.04 MW km^2. Fig. 12 shows the WPD maps per grid cell per district within the 10 regions of Ghana. The colour schemes are representative of the WPD value. From the map legend, red colour scheme represents areas with high WPD; with yellow to lemon-green representing low WPD values. The no data represents areas that are either unsuitable or with no identified input data. Fig. 11 is a visual geospatial model used in estimating the theoretical potential (see Figs. 11 and 12).

3.2. Geographical potential assessment

The first reduction of the theoretical wind power potential is the geographical restriction of areas that are or may not be conducive or appropriate for siting a wind turbine. The geographical potential as described earlier refers to the available land areas that are suitable for wind turbine installation and this is basically the necessary environmental and topographic conditions of the land that must either be present or absent in order to ensure the optimal production of wind energy and functioning of the wind turbine.

Results of the analysis indicate that, the windiest areas are located along the coastal areas, and along the mountain ranges such as the Akwapim-Togo Ranges, precisely the Kwahu Plateau in the middle belt region, and around the Gambaga escarpment in the North-East. From the district dataset used [48], the total geo-land mass of Ghana is about 231,650 km^2 [65,66], and total restricted areas under consideration is about 33,000 km^2. Thus, about 86% of the total land area (198, 649 km^2) of Ghana is geographically ideal for wind energy production. It must however be emphasized that, due to data constraints, the district administrative boundaries and polygon area used are not the latest and hence any future updated datasets may show discrepancies in results of analysis, thus the

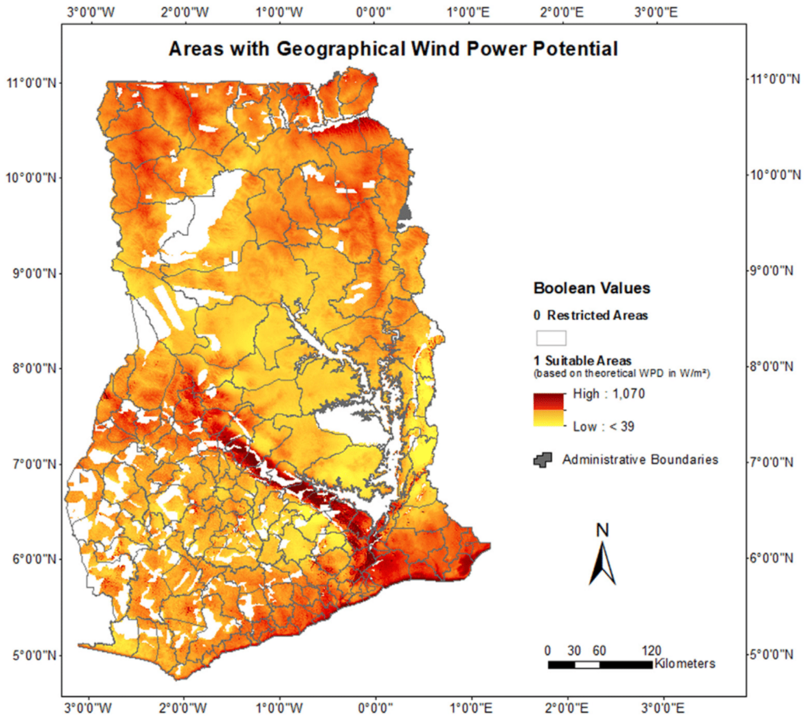


Fig. 13. Map showing areas with geographical potential.

results of this analysis is solely indicative and representative of the base year datasets used (Fig. 13).

3.3. Technical potential assessment

The next reduction of the wind power potential after the geographical potential, is the amount of wind energy that the turbine can produce per number of hours in a full year. This reduction is based on the requirements and specifications of the chosen wind turbine which is largely dependent on the power curve, the rated power, and the swept area of the turbine (V52/850).

However, to estimate the energy potential of the turbine of the available suitable land per grid cell, the wind power density is a crucial variable to consider [31]. The energy potential per grid cell is the product of the WPD per cell and the rated power of the wind turbine (i.e.850 kW). It must also be mentioned that, wind array efficiency of turbines was not considered since a single turbine model was used and the maximum energy output per grid cell within the suitable area was computed. The technical energy potential (GWh/year) by the turbine per grid cell of the suitable areas per district has been calculated (see Fig. 14).

From the analysis, areas along the coast especially districts within the Greater Accra Region show very high potential for wind energy development with annual energy production over 1,000 $GWhy^{-1}$; these include areas such as the Ada-Dangbe-East district, Ga South Municipal, etc. The Keta district in the Volta Region also shows good potential. In addition, in the Eastern Region, the stretch of area from the south-western to central-southern part has the highest potentials specifically within the Kwahu-South, Kwahu-East, Fanteakwa, and the Akwapim-North districts with over 2,000 $GWhy^{-1}$. In addition, areas in the Asante Region such as the southern part of Sekere-Central-West, Mampong Municipal, and Ejura-Sekyidumasi also show very good potential.

It is also important to state the differences in results between the turbine energy potential which uses the Weibull distribution and the theoretical potential estimations of the WPD which uses the Rayleigh distribution. For instance, the technical potential per cell for Kwahu East district in the Eastern region which has a maximum wind speed of 9.20 m/s generated turbine output of about 7000 GWh/year as compared to the Rayleigh estimate of about 6,700 GWh/year. In summary, the turbine optimization presents a percentage difference of about 2%. The percent difference is significant and thus, the Weibull distribution was preferred, especially for localised or micro-analysis.

In addition, it is important to reiterate that, the Weibull distribution curve was used to compute the technical WPD potential of the suitable areas. Also, the reduction in the technical WPD is because of the geographical restrictions that significantly reduced parts of the land area and by extension number of grid cells (land area) within some districts.

Finally, the study provides an estimation of total energy

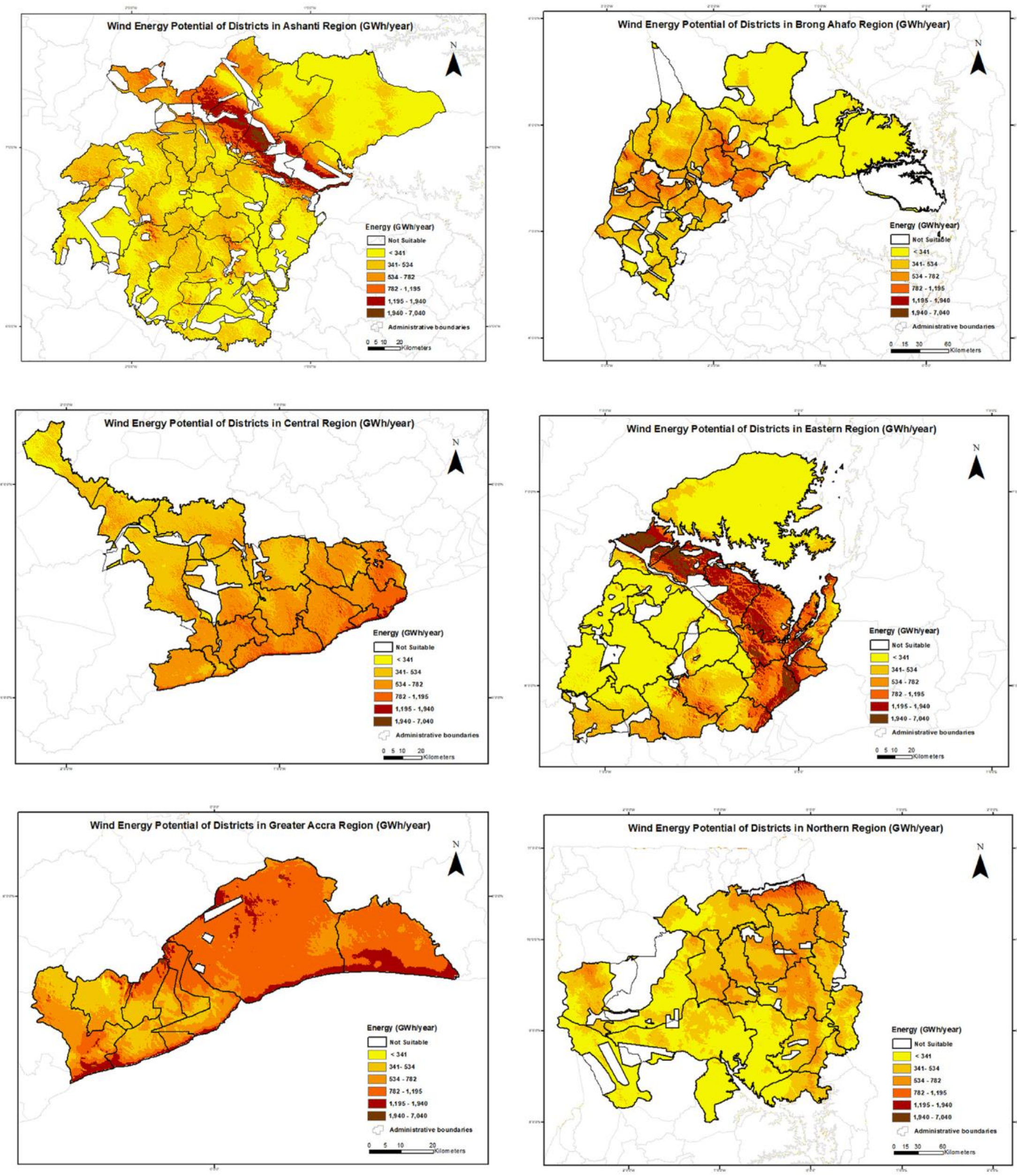


Fig. 14. Wind Energy Potential per District within the 10 regional boundaries of Ghana.

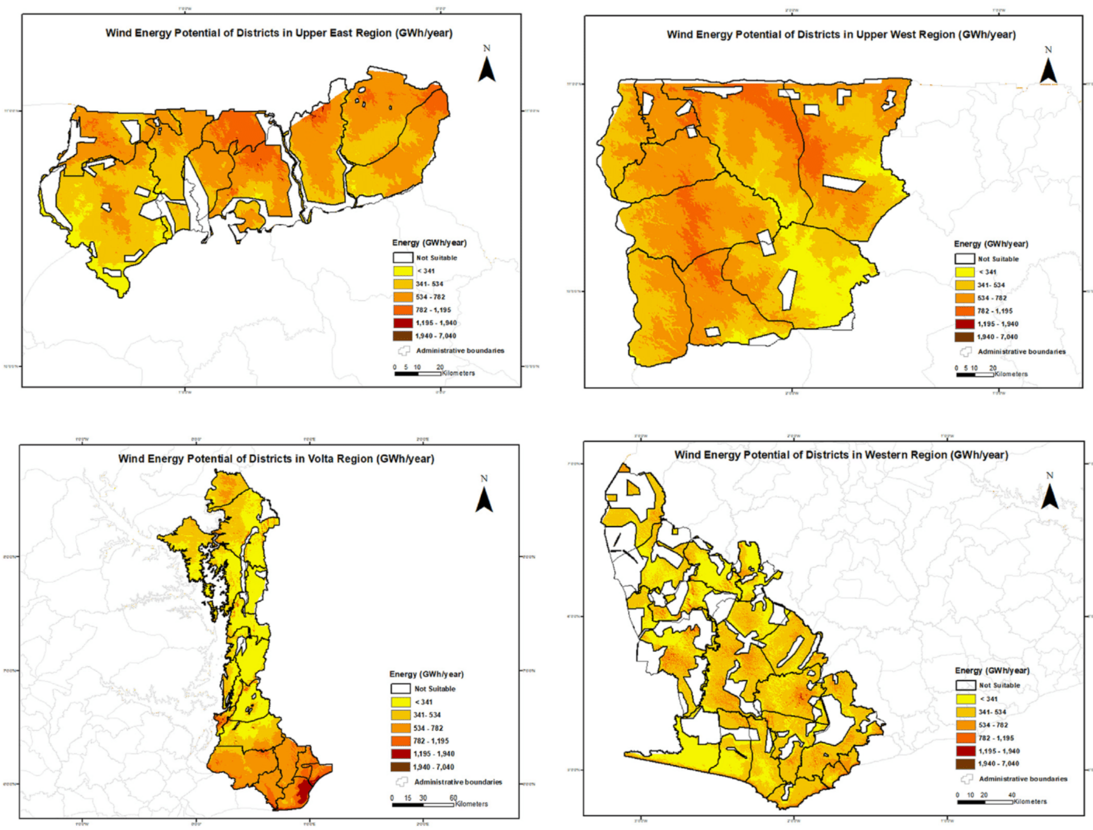


Fig. 14. (*continued*).

generated by each district that can be exploited with the corresponding total energy demand to bridge the access gap within the districts as shown in the Appendix A. For instance, the districts of Adaklu Anyigbe in the Volta region and the Sekyere Afram Plains in the Ashanti region with the lowest demand of 8 $GWhy^{-1}$ for both can be met with the wind energy generated there which is about 3000 GWh per annum for each. Again, the two most populous districts in Ghana which are the Accra Metro and Kumasi Metro have the highest annual demand of about 454 $GWhy^{-1}$ and 199 $GWhy^{-1}$, respectively. However, part of these demands can be met with generations in these districts, with generation of about 1800 $GWhy^{-1}$ and 463 $GWhy^{-1}$, respectively. The reason for this high demand is also because these are the most densely populated regional capitals in Ghana with very high population densities due to urbanisation. Accra Metro is the central district of the Greater Accra Region and the capital of Ghana.

3.4. Discussion

The general outlook of this study is to try and present wind energy as a viable sustainable energy transition option available to the government of Ghana towards the country's commitment to decarbonizing its energy system as well as serve as a development portfolio towards sustainable universal energy access in Ghana. To achieve this, the study tries to estimate the potential of wind energy that can be generated within the regional districts using combined geospatial and statistical approaches. Geospatial Multi-criteria method was used to process the input datasets that were secondarily sourced. Some datasets such as the wind speed and DEM were interpolated to fulfil some assumptions of the study which was to have the analysis at a square kilometre grid size. Analysis of the wind energy potential at this resolution provided more detail on the topography and also provided a much higher WPD compared to the initial higher resolutions of the input datasets [46].

The Weibull and the Rayleigh density functions were analysed and compared to ascertain which one yielded more power density at a localised level. The purpose of using these methods was solely to estimate the wind power potential per grid cell of the study area. Many authors who used these two methods and other statistical methods concluded and argued that, the Weibull function provided a better fit for wind speed distribution assessment and more relevantly, for estimating the wind power potential at a more localised level [30,33,34]. Thus, the Weibull density function was preferred and used because it presented a best fit for the wind speed distribution of Ghana with an average wind speed of about 5.4 ms^{-1} producing a power density of $124Wm^2$.

Besides, unlike other studies which focused mainly on wind energy assessment in some selected areas along the coast of Ghana [15,38,39], the general overview of the current study presents an assessment of wind energy potential for the entire onshore and more significantly at a disaggregate level (district level). It must also be emphasized that, different assumptions and multicriteria methods have been applied in previous studies and for the purpose of this study, the Boolean approach was used purposely to define suitable and restricted areas. Results from this study highlighted the fact that, some areas along the middle-belt show higher generation capacities compared to the coastal areas which have been the focus of many previous and similar studies in Ghana.

4. Conclusion

In summary, this study tries to estimate the wind energy potential in Ghana at the district level for the purpose of meeting the unmet demand in these areas with special attention to people living in off-grid areas by encouraging a distributed electricity system and to promote wind energy as a competitive RE option worth harnessing in Ghana. The assessment showed varying potentials that can be tapped. Even though most of government wind energy pilot projects have been carried out along the coastal areas, some areas in the middle-belt show higher generation capacities of over 2,000 $GWhy^{-1}$ per cell. On a large scale, about 300 TWh of wind energy can be generated annually in Ghana. It must also be highlighted that, to ensure optimal wind energy production, the geographical factors of the site are crucial but conservative and subjective. Thus, per this study, about 86% of Ghana's Onshore area - i.e. ~198, 649 km^2 of land area is geographically suitable for wind energy production. Total national theoretical Wind Power Density is approx. 0.04 MW km^2. But, in general, the wind speed potential of Ghana can be categorized as low. This general potential shows that, the wind speed characteristics of Ghana is more ideal for small-scale wind energy projects rather than large commercial wind farms.

Further research is encouraged to include or provide an assessment of the economic and implementation potential especially in developing countries, like Ghana. Other statistical methods other than the Weibull and the Rayleigh functions should be applied to future studies to compare the results of the energy output generated in Ghana. In addition, the GIS environment provides different approaches in computing the various methodology components, future research is encouraged to explore other geospatial techniques, especially at a more granular scale.

Credit author statement

This article was independently written by the author. All datasets used in the study are open-sourced and have duly been referenced. The ArcGIS software licence that was used for this study was provided by the University of Flensburg (Europa-Universität Flensburg).

Declaration of competing interest

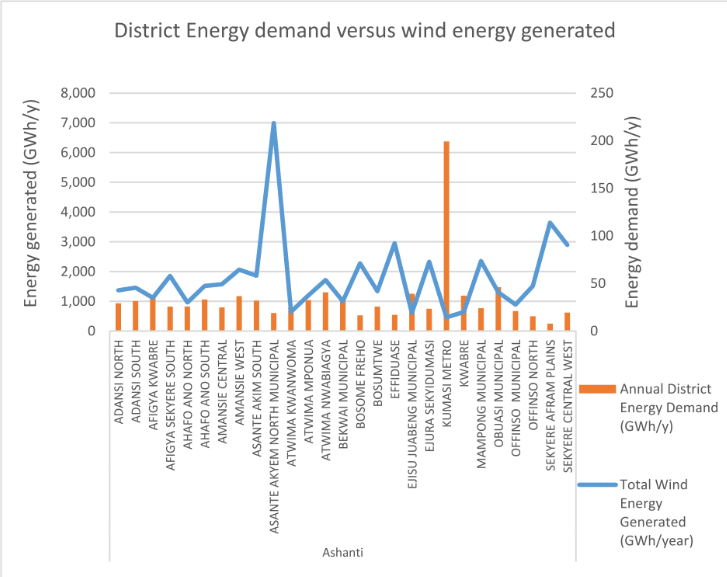
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

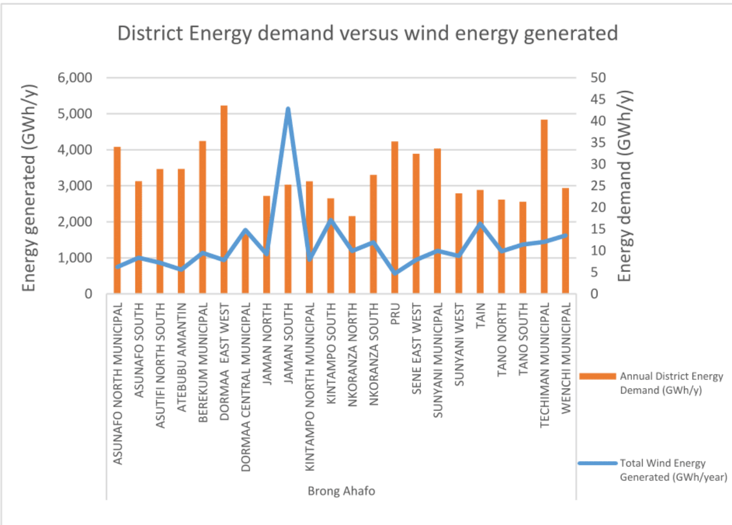
Acknowledgements

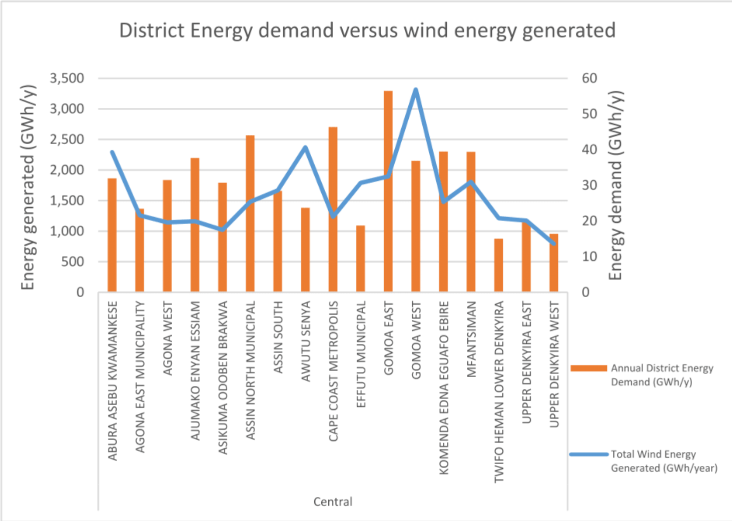
I would like to thank this journal and its anonymous reviewers for peer-reviewing this paper. Special thanks to my academic Supervisors. I am also grateful to family and friends for the continuous support and encouragement.

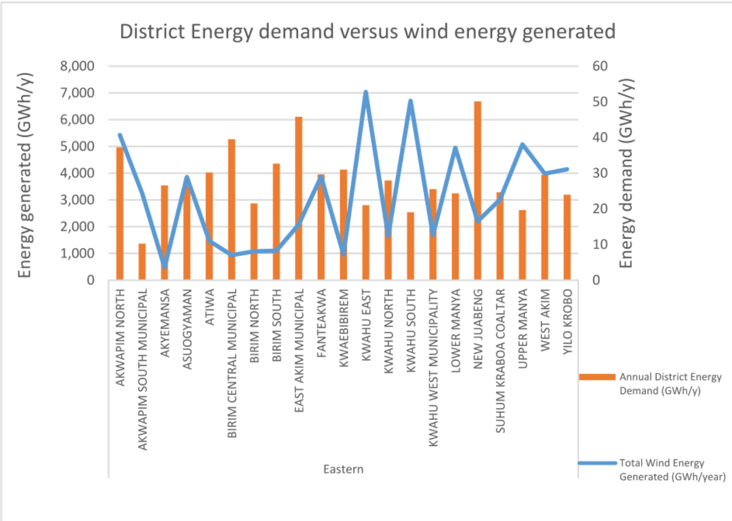
Appendix A

The charts below show the total annual wind energy that can be generated within the districts to meet the respective energy demand.

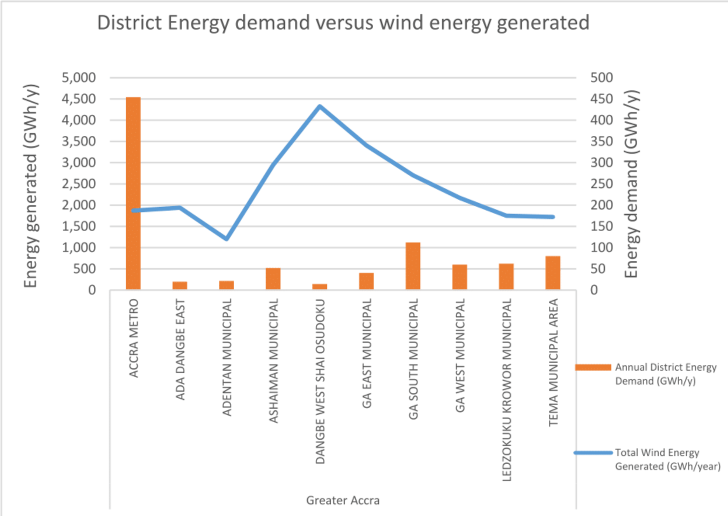


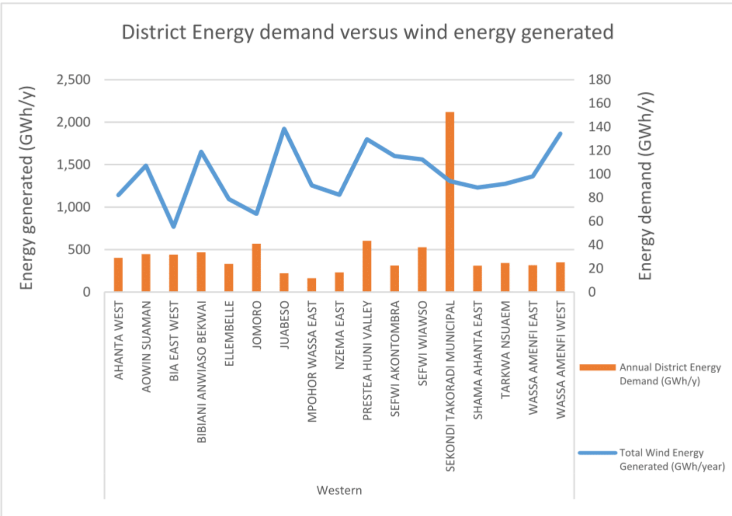



District Energy demand versus wind energy generated
Energy generated (GWh/y)
Energy demand (GWh/y)
3,500
3,000
2,500
2,000
1,500
1,000
500
0
60
50
40
30
20
10
0
ABURA ASEBU KWAMANKESE
AGONA EAST MUNICIPALITY
AGONA WEST
AJUMAKO ENYAN ESSIAM
ASIKUMA ODOBEN BRAKWA
ASSIN NORTH MUNICIPAL
ASSIN SOUTH
AWUTU SENYA
CAPE COAST METROPOLIS
EFFUTU MUNICIPAL
GOMOA EAST
GOMOA WEST
KOMENDA EDNA EGUAFO EBIRE
MFANTSIMAN
TWIFO HEMAN LOWER DENKYIRA
UPPER DENKYIRA EAST
UPPER DENKYIRA WEST
Central
Annual District Energy Demand (GWh/y)
Total Wind Energy Generated (GWh/year)

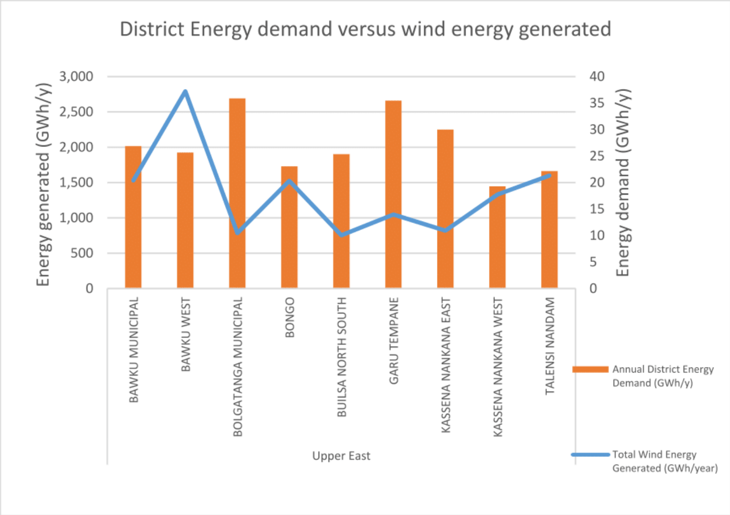

District Energy demand versus wind energy generated
Energy generated (GWh/y)
Energy demand (GWh/y)
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
60
50
40
30
20
10
0
AKWAPIM NORTH
AKWAPIM SOUTH MUNICIPAL
AKYEMANSA
ASUOGYAMAN
ATIWA
BIRIM CENTRAL MUNICIPAL
BIRIM NORTH
BIRIM SOUTH
EAST AKIM MUNICIPAL
FANTEAKWA
KWAEBIBIREM
KWAHU EAST
KWAHU NORTH
KWAHU SOUTH
KWAHU WEST MUNICIPALITY
LOWER MANYA
NEW JUABENG
SUHUM KRABOA COALTAR
UPPER MANYA
WEST AKIM
YILO KROBO
Eastern
Annual District Energy Demand (GWh/y)
Total Wind Energy Generated (GWh/year)

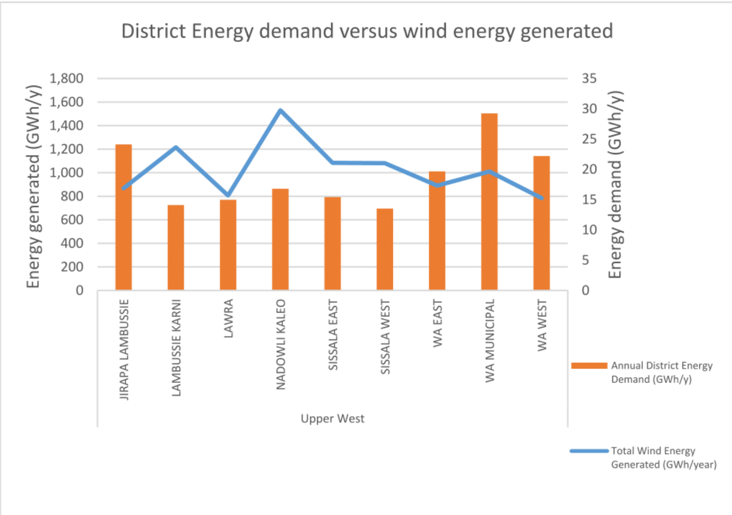
(***continued***).


District Energy demand versus wind energy generated
Energy generated (GWh/y)
Energy demand (GWh/y)
5,000
4,500
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
500
450
400
350
300
250
200
150
100
50
0
ACCRA METRO
ADA DANGBE EAST
ADENTAN MUNICIPAL
ASHAIMAN MUNICIPAL
DANGBE WEST SHAI OSUDOKU
GA EAST MUNICIPAL
GA SOUTH MUNICIPAL
GA WEST MUNICIPAL
LEDZOKUKU KROWOR MUNICIPAL
TEMA MUNICIPAL AREA
Greater Accra
Annual District Energy Demand (GWh/y)
Total Wind Energy Generated (GWh/year)

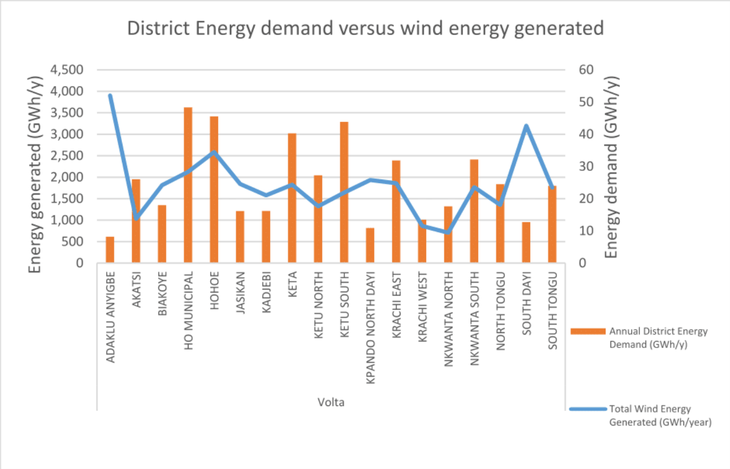

District Energy demand versus wind energy generated
Energy generated (GWh/y)
Energy demand (GWh/y)
2,500
2,000
1,500
1,000
500
0
180
160
140
120
100
80
60
40
20
0
AHANTA WEST
AOWIN SUAMAN
BIA EAST WEST
BIBIANI ANWIASO BEKWAI
ELLEMBELLE
JOMORO
JUABESO
MPOHOR WASSA EAST
NZEMA EAST
PRESTEA HUNI VALLEY
SEFWI AKONTOMBRA
SEFWI WIAWSO
SEKONDI TAKORADI MUNICIPAL
SHAMA AHANTA EAST
TARKWA NSUAEM
WASSA AMENFI EAST
WASSA AMENFI WEST
Western
Annual District Energy Demand (GWh/y)
Total Wind Energy Generated (GWh/year)

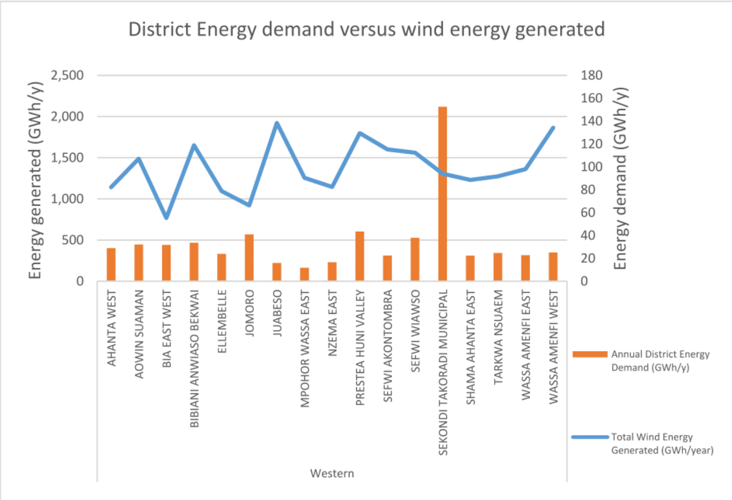
(*continued*).


District Energy demand versus wind energy generated
Energy generated (GWh/y)
Energy demand (GWh/y)
3,000
2,500
2,000
1,500
1,000
500
0
40
35
30
25
20
15
10
5
0
BAWKU MUNICIPAL
BAWKU WEST
BOLGATANGA MUNICIPAL
BONGO
BUILSA NORTH SOUTH
GARU TEMPANE
KASSENA NANKANA EAST
KASSENA NANKANA WEST
TALENSI NANDAM
Upper East
Annual District Energy Demand (GWh/y)
Total Wind Energy Generated (GWh/year)


District Energy demand versus wind energy generated
Energy generated (GWh/y)
Energy demand (GWh/y)
1,800
1,600
1,400
1,200
1,000
800
600
400
200
0
35
30
25
20
15
10
5
0
JIRAPA LAMBUSSIE
LAMBUSSIE KARNI
LAWRA
NADOWLI KALEO
SISSALA EAST
SISSALA WEST
WA EAST
WA MUNICIPAL
WA WEST
Upper West
Annual District Energy Demand (GWh/y)
Total Wind Energy Generated (GWh/year)

(*continued*).





(***continued***).

References

[1] Adaramola MS, Quansah DA, Agelin-Chaab M, Paul SS. Multipurpose renewable energy resources based hybrid energy system for remote community in northern Ghana. Sustainable Energy Technologies and Assessments 2017;22: 161–70. https://doi.org/10.1016/j.seta.2017.02.011.

[2] Adair-Rohani H, et al. Limited electricity access in health facilities of sub-Saharan Africa: a systematic review of data on electricity access, sources, and reliability. Global health, science and practice 2013;1(2):249–61. https://doi.org/10.9745/GHSP-D-13-00037.

[3] Khandker SR, Samad HA, Ali R, Barnes DF. Who benefits most from rural electrification? Evidence in India. " License: CC BY 3.0 IGO, 2012. [Online]. Available: https://openknowledge.worldbank.org/handle/10986/9328.

[4] Energia. Research project 7: building the evidence base for women's empowerment and entrepreneurship to improve energy interventions' effectiveness - energia (accessed: Feb. 16 2021), https://www.energia.org/project/building-the-evidence-base-for-womens-empowerment-and-entrepreneurship/.

[5] The World Bank. "Tracking SDG7: the energy progress report. 2018.

[6] UNFCCC, *Nationally Determined Contributions (NDCs)*. accessed: Feb. 17 2021), https://unfccc.int/process-and-meetings/the-paris-agreement/nationally-determined-contributions-ndcs/nationally-determined-contributions-ndcs.

[7] Adobea Oduro M, Gyamfi S, Asumadu Sarkodie S, Kemausuor F. Evaluating the success of renewable energy and energy efficiency policies in Ghana: matching the policy objectives against policy instruments and outcomes. In: Al Qubeissi M, El-kharouf A, Serhad Soyhan H, editors. Renewable energy: resources, challenges and applications/edited by mansour Al qubeissi, ahmad el-kharouf, hakan serhad soyhan. London: IntechOpen; 2020.

[8] Gyamfi S, Modjinou M, Djordjevic S. "Improving electricity supply security in Ghana—the potential of renewable energy. Renew Sustain Energy Rev 2015;43:1035–45. https://doi.org/10.1016/j.rser.2014.11.102.

[9] IPCC. Renewable energy sources and climate change mitigation. Special report of the intergovernmental panel on climate change. Technical support unit working group III Potsdam Institute for Climate Impact Research. PIK); 2011.

[10] Energy Commission of Ghana. "NATIONAL energy statistics : 2007 - 2016. 2017.

[11] Energy Commission of Ghana. 2018 energy (supply and demand) outlook for Ghana. 2018.

[12] Obeng-Darko NA. Why Ghana will not achieve its renewable energy target for electricity. Policy, legal and regulatory implications. Energy Pol 2019;128: 75–83. https://doi.org/10.1016/j.enpol.2018.12.050.

[13] Climate Investment Fund. "Scaling-up renewable energy program in Ghana joint mission,". https://www.climateinvestmentfunds.org/sites/cif_enc/files/AM%20SREP%20Ghana%20Joint%20Mission.pdf; 2015.

[14] Sakah M, Diawuo FA, Katzenbach R, Gyamfi S. Towards a sustainable electrification in Ghana: a review of renewable energy deployment policies.

Renew Sustain Energy Rev 2017;79:544–57. https://doi.org/10.1016/j.rser.2017.05.090.
[15] Adaramola MS, Agelin-Chaab M, Paul SS. Assessment of wind power generation along the coast of Ghana. 2014. https://www.sciencedirect.com/science/article/pii/S0196890413005426/pdfft?isDTMRedir=true&download=true.
[16] World Bank. Sustainable energy for all (SE4ALL) database from the SE4ALL global tracking framework led jointly by the World Bank, international energy agency, and the energy sector management assistance program Access to electricity (% of population), Data. Available: https://data.worldbank.org/indicator/eg.elc.accs.zs. [Accessed 29 June 2020].
[17] IEA. Energy access outlook 2017:: World energy outlook special report. Available: https://www.iea.org/reports/energy-access-outlook-2017. [Accessed 29 June 2020].
[18] Energy Commission of Ghana. "SE4ALL-Ghana action plan: Ghana – action plan for sustainable energy for all by 2030,". 2012. Available: http://energycom.gov.gh/files/SE4ALL-GHANA%20ACTION%20PLAN.pdf.
[19] GWEC. Global wind report - annual market update 2012. 2012. https://www.gwec.net/wp-content/uploads/2012/06/Annual_report_2012_LowRes.pdf.
[20] Edenhofer O, Pichs-Madruga R, Sokona Y, Seyboth K, Matschoss P, Kadner S. Special report on renewable energy sources and climate change mitigation: summary for policymakers and technical summary. 2012.
[21] IRENA, "Ghana Renewables Readiness Assessment, 2015.
[22] Park GL, Schäfer AI, Richards BS. Potential of wind-powered renewable energy membrane systems for Ghana. Desalination 2009;248(1–3):169–76. https://doi.org/10.1016/j.desal.2008.05.053.
[23] Energy commission of Ghana, "Ghana renewable energy masterplan. http://www.energycom.gov.gh/files/Renewable-Energy-Masterplan-February-2019.pdf; 2019.
[24] Schillings C, Meyer R, Trieb F. Solar and wind energy resource assessment (SWERA): *high resolution solar radiation Assessment for Ghana*. 2004. http://swera.unep.net/.
[25] Lackner AM, et al. Uncertainty analysis in wind resource assessment and wind energy production estimation. 2007.
[26] Rodríguez O, del Río JA, Jaramillo OA, Martínez M. Wind power error estimation in resource assessments. PloS One 2015;10(5):e0124830. https://doi.org/10.1371/journal.pone.0124830.
[27] Energy Commission of Ghana. Barriers to renewable energy technology transfer in Ghana. 2015. http://energycom.gov.gh/files/Barriers%20to%20Renewable%20Energy%20Technology%20Transfer%20in%20Ghana(2015).pdf.
[28] Archer Cristina L, Jacobson Mark Z. Evaluation of global wind power. J Geophys Res 2005;110:D12. https://doi.org/10.1029/2004JD005462.
[29] Mert İ, Karakuş C. A statistical analysis of wind speed data using Burr, generalized gamma, and Weibull distributions in Antakya, Turkey. Turk J Electr Eng Comput Sci 2015;23:1571–86. https://doi.org/10.3906/elk-1402-66.
[30] Manwell, J. F. and McGowan, J. G, Wind energy explained:: Theory, Design and Application. [Online]. Available: https://scholar.google.com/scholar_lookup?title=Wind%20energy%20explained%3A%20theory%2C%20design%20and%20application&author=J.F.%20Manwell&publication_year=2009 (accessed: Oct. 9 2019).
[31] Hoogwijk M, de Vries B, Turkenburg W. Assessment of the global and regional geographical, technical and economic potential of onshore wind energy. Energy Econ 2004;26(5):889–919. https://doi.org/10.1016/j.eneco.2004.04.016.
[32] Kumar MBH, Balasubramaniyan S, Padmanaban S, Holm-Nielsen JB. Wind energy potential assessment by Weibull parameter estimation using multiverse optimization method: a case study of Tirumala region in India. Energies 2019;12(11):2158. https://doi.org/10.3390/en12112158.
[33] Albani A, Ibrahim M. Wind energy potential and power law indexes assessment for selected near-coastal sites in Malaysia. Energies 2017;10(3):307. https://doi.org/10.3390/en10030307.
[34] Mentis D, Hermann S, Howells M, Welsch M, Siyal SH. Assessing the technical wind energy potential in Africa a GIS-based approach. Renew Energy 2015;83:110–25. https://doi.org/10.1016/j.renene.2015.03.072.
[35] Janke JR. Multicriteria GIS modeling of wind and solar farms in Colorado. Renew Energy 2010;35(10):2228–34. https://doi.org/10.1016/j.renene.2010.03.014.
[36] Baffoe PE, Sarpong D. Selecting suitable sites for wind energy development in Ghana. Ghana Mining Journal 2016;16(1):8. https://doi.org/10.4314/gmj.v16i1.2.
[37] International Renewable Energy Agency (IRENA). Estimating the renewable energy potential in Africa: a GIS-based approach. 2014.
[38] Asumadu-Sarkodie S, Owusu PA. "The potential and economic viability of wind farms in Ghana," *Energy Sources, Part A: recovery, Utilization*. and Environmental Effects 2016;38(5):695–701. https://doi.org/10.1080/15567036.2015.1122680.
[39] Essandoh E, Osei YE, Adam WF. Prospects OF wind power generation IN Ghana. https://www.researchgate.net/publication/299414551_PROSPECTS_OF_WIND_POWER_GENERATION_IN_GHANA.
[40] HDX. Ghana - administrative boundaries - humanitarian data exchange. accessed: Jun. 29 2020), https://data.humdata.org/dataset/ghana-administrative-boundaries.
[41] World Bank/ESMAP. Beyond connections : energy access redefined: *introducing multi -tier Approach to measuring energy access*. 2015 [Online]. Available: https://www.worldbank.org/en/topic/energy/publication/energy-access-redefined.
[42] ESMAP. Multi-tier framework (MTF). accessed: Jun. 30 2020), https://www.esmap.org/node/71201.
[43] Ghana Statistical Service. Ghana living standards survey round 6.: *(GLSS 6) main report*. 2014.
[44] Fernández RD, Mantz RJ, Battaiotto PE. Linear and non-linear control of wind farms. Contribution to the grid stability. Int J Hydrogen Energy 2010;35(11):6019–24. https://doi.org/10.1016/j.ijhydene.2009.12.084.
[45] L. Bauer, Vestas V52 - 850,00 kW - Wind turbine. [Online]. Available: https://en.wind-turbine-models.com/turbines/71-vestas-v52 (accessed: Oct. 3 2020).
[46] DTU, Global Wind Atlas. [Online]. Available: https://globalwindatlas.info/en/ (accessed: Jul. 1 2020).
[47] Geography of Ghana - Geographical Regions. Rivers and lakes, climate. accessed: Jul. 1 2020, http://worldfacts.us/Ghana-geography.htm.
[48] Ghana Open Data Initiative. https://data.gov.gh/search/type/dataset?query=districts&sort_by=changed&sort_order=DESC. [Accessed 14 May 2020].
[49] Wijk A, Coelingh JP, Energieonderzoek Stichting. Centrum Nederland. Rijksuniversiteit te Utrecht., *Wind power potential in the OECD countries*. Utrecht the Netherlands: Department of Science Technology and Society Utrecht University; 1993. http://worldcatlibraries.org/wcpa/oclc/262847400.
[50] Esri. Cell size and resampling in analysis—ArcGIS help | documentation. accessed: Mar. 11 2020), https://desktop.arcgis.com/en/arcmap/latest/extensions/spatial-analyst/performing-analysis/cell-size-and-resampling-in-analysis.htm.
[51] Justus CG. Winds and wind system performance. Philadelphia, PA: Franklin Institute Press; 1978.
[52] Hughes Tim. "Determining wind power density and wind power classes from wind speed information,". http://educypedia.karadimov.info/library/Lesson3_WPD_windclass.pdf; 2000.
[53] Floors R, Nielsen M. Estimating air density using observations and Re-analysis outputs for wind energy purposes. Energies 2019;12(11):2038. https://doi.org/10.3390/en12112038.
[54] Zhang J, Chowdhury S, Messac A, Castillo L. A multivariate and multimodal wind distribution model. Renew Energy 2013;51:436–47. https://doi.org/10.1016/j.renene.2012.09.026.
[55] Kutz M, Mechanical engineers' handbook, volume 4: energy and power (accessed: Jan. 29 2020).
[56] Cliff CW. The effect of generalized wind characteristics on annual power estimates from wind turbine generators. 1977.
[57] Asare-Addo M. Air density - Ghana, vol. 1. Mendeley Data; 2021. https://doi.org/10.17632/9ck8478g65.1. https://doi.org/10.17632/9ck8478g65.1.
[58] Wind energy resource Atlas of the United States (accessed: Jan. 29 2020), https://rredc.nrel.gov/wind/pubs/atlas/tables/1-1T.html.
[59] Sahani Shubhasmita, Prasad Hari Shankar, Raghavaswamy V. "Location-of-Solid-Waste-Disposal-Site-using-Remote-Sensing-GIS-MCDA-Techniques-in-Madanapalle-Municipality-Andhra-Pradesh,". https://www.researchgate.net/profile/Shubhasmita_Sahani2/publication/280066457_Location_of_Solid_Waste_Disposal_Site_using_Remote_Sensing_GIS_MCDA_Techniques_in_Madanapalle_Municipality_Andhra_Pradesh/links/55a638db08aeb00df2321cdf/Location-of-Solid-Waste-Disposal-Site-using-Remote-Sensing-GIS-MCDA-Techniques-in-Madanapalle-Municipality-Andhra-Pradesh.pdf.
[60] Tim Höfer, Sunak Yasin, Siddique Hafiz, Madlener Reinhard. Wind farm siting using a spatial analytic hierarchy wind farm siting using a spatial analytic hierarchy process approach: a case study of the städteregion aachen. FCN Working 2014. Paper No. 16/2014.
[61] Baban SM, Parry T. Developing and applying a GIS-assisted approach to locating wind farms in the UK. Renew Energy 2001;24(1):59–71. https://doi.org/10.1016/S0960-1481(00)00169-5.
[62] Tegou L-I, Polatidis H, Haralambopoulos DA. Environmental management framework for wind farm siting: methodology and case study. J Environ Manag 2010;91(11):2134–47. https://doi.org/10.1016/j.jenvman.2010.05.010.
[63] Esri, 30 arc-second DEM of Africa (Data Basin Dataset): 30 arc-second DEM of Africa (Data Basin Dataset). [Online]. Available: https://www.arcgis.com/home/item.html?id=c891f64c13be4a2c96491e386bfed8c5 (accessed: Apr. 8 2020).
[64] Höfer T, Sunak Y, Siddique H, Madlener R. Wind farm siting using a spatial Analytic Hierarchy Process approach: a case study of the Städteregion Aachen. Appl Energy 2016;163:222–43. https://doi.org/10.1016/j.apenergy.2015.10.138.
[65] Unep-Wcmc. World Database on protected areas user manual 1.4. ": UNEP-WCMC.; 2016.
[66] Protected Planet. [Online]. Available: https://www.protectedplanet.net/ (accessed: Apr. 8 2020).
[67] Johnson GL. Wind energy systems. NJ. Englewood Cliffs: Prentice Hall; 1985.
[68] Rohatgi JS, Nelson V. Wind characteristics: an analysis for the generation of wind power. 1994. Canyon, TX.
[69] Iso, Iso/Iec 27001. Information technology — security techniques — information security management systems — Requirements (accessed: Feb. 4 2020), https://www.iso.org/standard/54534.html; 2013.

Paper 2:

Optimal techno-economic potential and site evaluation for solar PV and CSP systems in Ghana. A geospatial AHP multi-criteria approach[5]

[5] referenced as: M. Asare-Addo, "Optimal techno-economic potential and site evaluation for solar PV and CSP systems in Ghana. A geospatial AHP multi-criteria approach," Renewable Energy Focus, vol. 41, pp. 216–229, 2022, doi: 10.1016/j.ref.2022.03.007

Renewable Energy Focus 41 (2022) 216–229

Contents lists available at ScienceDirect

Renewable Energy Focus

journal homepage: www.elsevier.com/locate/ref

Research Paper

Optimal techno-economic potential and site evaluation for solar PV and CSP systems in Ghana. A geospatial AHP multi-criteria approach

Mary Asare-Addo

Europa-Universität Flensburg, Department of Energy and Environmental Management, Munketoft 3 B, 24937 Flensburg, Germany

A R T I C L E I N F O

Article history:
Received 25 February 2022
Revised 21 March 2022
Accepted 21 March 2022
Available online 28 March 2022

Keywords:
Geospatial
Analytic hierarchy process
Solar PV
CSP
Ghana

A B S T R A C T

In this study, the techno-economic potential and site suitability for utility-scale solar PV and CSP technologies have been estimated for Ghana. The overarching goal is to increase visibility of solar energy potentials to encourage and facilitate the uptake of renewable energy towards the global decarbonisation agenda as well as to expand energy access in the country. To assist policymakers in Ghana towards this agenda including potential areas for investment, the geographical, technical, and economic potentials for the two solar energy technology solutions have been assessed. In this study unlike many other studies, the AHP and Weighted Sum Average approaches have been applied in the ArcGIS Pro environment to estimate the two technology potentials at the national and regional levels. This combined approach is still in its infantry stages and thus contributes to a new body of knowledge from the international perspective in addition to its applicability at specific country level like Ghana. Results from the analysis show varying generation capacities for the selected solar energy technologies. Geographically, about 85% of total land area in Ghana is suitable for solar energy deployment. At the national level, a generation capacity of ~68,622 TWh/year can be harnessed from utility-scale PV and ~23,452 TWh/year from CSP systems. The LCOE for the utility-scale solar PV technology ranges from a minimum of about \$0.04/kWh to a maximum of \$0.15/kWh, and from ~\$0.73/kWh to ~\$2.89/kWh for the CSP technology in Ghana.

Introduction

Access to energy or electricity is a basic need of every human being as stated in UN Agenda 2030 and central to achieving the Sustainable Energy for All (SE4ALL) initiative with focus on SDG 7 [1–4]. Access to energy is an enabler for sustainable development and thus, plays an integral role in the development of a country. It is one of the major economic boosters and development indicators of a country. According to the World Bank and Sustainable Energy for All organizations, about 17% of the Ghanaian population lived without electricity access in 2019 [5]. Energy consumption in Ghana on the average is 50-100 times lower than in developed countries [6,7]. For instance, in 2018, annual electricity consumption per capita in Ghana was only 0.3 MWh/capita compared to in developed countries like Germany with 6.9 MWh/capita, and 13.1 MWh/capita in the USA [8]. Even though there is no universally accepted threshold of the minimum accepted consumption per capita value, experts like Javadi, et al. [9] posits that, an assessment between basic quality of life, basic survival, internal collaboration and social graces, "annual electricity consumption of about 1000 kWh per year per capita is known as the boundary between basic life condition and guaranteed survival" [9,10].

Efforts by the government of Ghana towards increasing electricity access dates to the 1960s, when the then government developed one of the country's ambitious electrification plans through the development of hydroelectric power projects. This led to the development of the Akosombo Dam across the Volta River [11,12] the major hydro-electric power plant in the country. Following, the country saw an increase in the development of two additional mini-hydro power plants, the Kpong and Bui hydro power stations, making hydropower the second major share and source of clean energy in the country's energy generation mix. This accounted for about 40% of total installed generation capacity of which Akosombo supplied about 1020 MW; Kpong 160 MW, and Bui 40 MW as at 2018 [12]. Also, as of 2018, grid capacity was about 14,067 GWh of which 39.2% (i.e., 4991 GWh) came from hydropower.

However, currently with the impact of climate change, the capacity of hydro has significantly reduced because of shortage of water inflow into the dams. Consequently, with an existing and increasing demand, the country was compelled to find additional power sources to bridge the huge demand and supply gap. The government then resorted to fossil fuels in its quest to service the unmet energy demands in the country thereby increasing the share and making thermal power the major source of electricity

E-mail address: mary.asare-addo@studierende.uni-flensburg.de

https://doi.org/10.1016/j.ref.2022.03.007
1755-0084/

Nomenclature

AHP	Analytic Hierarchy Process	MCDM	Multi-criteria decision-making
CI	Consistency Index	MW	Megawatt
CR	Consistency Ratio	MWh	Megawatt hour
CSP	Concentrated Solar Power	NDC	Nationally Determined Contribution
DNI	Direct Normal Irradiance	O&M costs	Operations and Maintenance costs
ELECTRE	ELimination Et Choix Traduisant la REalité	PROMETHEE	Preference Ranking Organization METHod for Enrichment of Evaluations
EU	European Union	PR_{pv}	Performance Ratio of photovoltaic module
FAHP	Fuzzy Analytic Hierarchy Process	RE	Renewable energy
GHI	Global Horizontal Irradiance	RI	Random Index
GIS	Geographic Information Systems	SAM	System Advisor Model
GSA	Global Solar Atlas	SDG 7	Sustainable Development Goal 7
GWh	Gigawatt hour	SE4ALL	Sustainable Energy for All
GWh/y	Gigawatt hour per year	Solar PV	Solar Photovoltaics
IRENA	International Renewable Energy Agency	TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
IUCN	International Union for Conservation of Nature	TWh/year	Terawatt hour per year
Km	Kilometer	UN	United Nations
km^2	Square kilometer	UNEP	United Nations Environment Programme
kW	Kilowatt	WCMC	World Conservation Monitoring Centre
kWh	Kilowatt hour	$	United States Dollar
$kWh/m^2/year$	Kilowatt hour per square meter per year		
LCOE	Levelized cost of electricity		

supply in the country [1,13–15]. As at 2020, thermal power accounted for about 67.91% of grid electricity supply in the country [13], hydro generation at 31.79% of hydro; with still insignificant share of 0.30% from solar photovoltaics (PV) [13]. More so, even with the additional supply, the country is still unable to meet the basic electricity needs of the people.

Further, with increasing concern about the use of conventional energy sources contributing to greenhouse gas emissions and an environmental pollutant, the use of renewable energy (RE) technologies like solar, wind, hydro, etc., have gained prominence and political attention. Also, without global transitioning of the energy sector, it will be impossible to achieve the 1.5 degree target of the Paris Agreement [16]. More significantly, also because renewable energy generation costs have experienced a sharp fall over the past decade due to economies of scale, technology improvement, growing developer experiences as well as a growing competitive supply chain in the RE industry globally [17 18] making RE a more competitive alternative energy source. Again, according to IRENA [17], renewable energy technologies have become the least-cost option for alternative supply in almost all parts of the world with about 72% increasing deployment in 2019. Levelized cost of electricity (LCOE) for utility-scale solar PV fell 82% between 2010 and 2019, whereas that of concentrated solar power (CSP) fell 47% as reported by IRENA [17]. The call to diversify the country's energy system using RE resources has even become more crucial for three main reasons; i) to assist the government of Ghana meet its sustainable energy for all Nationally Determined Contribution (NDC) targets by 2030 [1], ii) in fulfilment of its Paris Agreement commitments to contribute and reduce its greenhouse emission, iii) and help cut-down investment costs accrued in importing crude oil to fuel existing thermal plants which will eventually assist government achieve its debt recovery in the energy sector [19,20].

Just like many RE resources, solar energy development involves strong geospatial implication [21]. Solar radiation intensities vary considerably from one location to another. For instance, according to IRENA's CSP technology brief, unlike solar PV systems, CSP plants require high direct solar irradiance for the plants to work and as such one of the major reasons places in the Sun Belt region (.i.e. between 40 degrees north and south of the equator) show good potential for CSP deployment [22]. This implies that the selection of a suitable site for solar energy planning requires consideration for certain fundamental conditions that the chosen site must fulfil to ensure optimal solar energy generation. These criteria may include but not limited to, proximity to the grid infrastructure for large scale or utility grid-connected systems as well as considerations to how to provide cost-effective options for the end-user while minimizing the overall production costs of the project and maximizing energy output from the solar technology used [23].

The geographical location of Ghana provides the country with an excellent potential for solar energy development [24]. And thus, performing a thorough solar energy site assessment is a strategic step towards ensuring a well-performing and cost-effective solar energy project [23]. Furthermore, as mentioned earlier, the geographical characteristics of solar irradiance has led to a growing importance in geospatial-based studies in estimating the solar energy potential of a location and help determine a more viable solution to service both urban and off-grid or rural households [25]. Moreover, the development of many solar technologies for a site is mostly backed by policy programs and decisions to assist policymakers make a well-informed decision towards their sustainable energy access interventions and programmes. Multi-criteria decision-making (MCDM) methods have helped to make decisions when confronted with multiple and conflicting objectives [26]. More so, to assist policymakers achieve this goal, several geographic information systems (GIS) based multi-criteria decision-making approaches have been applied to help determine the best site for the development of a specific type of solar technology; in this case for utility-scale PV and CSP technologies.

The application of GIS-based MCDM method has been used in several studies to assess potential sites for solar energy projects. For instance, Wang, Jing et al. [27]; Kumar, Sah et al. [28]; and Choi, Suh et al. [29] have provided an extensive review of different MCDM methods for RE resource mapping and planning across different geographies. Some methods highlighted included the Analytic Hierarchy Process (AHP) by Saaty [30], FAHP by Zadeh [31], Weighted Sum Model by Fishburn [32], Weighted Average by Anderson [33], Boolean Overlay [34], Weighted Product Model by Bridgman [35]; ELECTRE by Benayoun et al. [36], TOPSIS by Hwang and Yoon [37]; Multi-Attribute Utility Technique by Edwards and Newman [38], PROMETHEE by Brans and Vincke [39], and Hierarchical Cluster Analysis [40], etc. These methods have been applied in various studies in many countries such as South Africa [41,42]; in Turkey [43], Croatia [44], West Africa [7], Canada [45], USA [46], just to mention a few.

Despite all the MCDM techniques, the most widely used is the AHP technique developed by Thomas, L. Saaty [30]. However, despite the usefulness of the AHP method, it is not comprehensive on its own without the application of additional decision-making methods [28]. For instance, the AHP approach alone does not address the geographical conditions of the location. Many studies have combined AHP with other methods like the fuzzy logic, Goal Programming etc., to reduce the complexity when applied to a number of criteria [47]. The application of AHP method combined with GIS techniques have been applied in many solar energy evaluation studies, for example, in Saudi Arabia [23,48], in Indonesia [49,50], in China [51], Morocco [52], Brazil [53], Japan and Malaysia [54] etc. Colak, Memisoglu et al.[43] applied GIS and the AHP methods to select optimal site for solar PV power plants in the Malatya Province in Turkey. The GIS-AHP approach has also been applied to explore the potential of CSP in Zimbabwe [55], and solar energy potential in the Bumthang Valley in Bhutan [56]. Yushchenko et al. [7] also carried out a GIS-based evaluation of solar PV and CSP potential in the West Africa region which included Ghana. In the present study unlike many other studies, the AHP and Weighted Sum Average approaches have been applied; this combined approach is still in its infantry stages and thus contributes to a new body of knowledge from the international perspective in addition to its applicability at specific country levels. Further, a review of the literature shows that, this study and approach is the first of its kind in Ghana providing and considering a multi-criteria and multi-dimensional approaches by taking into account the national electrification policy which is to extend grid connection to areas within a 20km distance with a population density of 500persons/ km^2 and above who live within the 20km existing grid buffer distance [57,58].

In addition, one key aspect missing in most of the studies mentioned above is an assessment of the financial viability of the solar project at specific locations. To address this, the LCOE method which is a measure of the lifetime costs of generating electricity from energy technologies has been used by many experts [59–61] to model the potential costs involved in embarking on solar projects. Researches done by the EU solar bankability project [60] and, IRENA [61] have used and established a common practice using the LCOE method to minimize the risks associated with investments in solar PV and CSP projects. In a techno-economic feasibility study on CSP by Aly, Bernardos et al., [69] in Tanzania, they reiterated that the penetration of CSP projects in Tanzania is however dependent on the associated financial implications. Furthermore, even in studies where the LCOE method has been used to compute the life-cycle costs of solar project, an assessment of the geographical viability is usually not included or evaluated. Many of the solar energy assessments are based on an either-or approach, i.e., it is either purely a techno-economic assessment or just an evaluation of the geographical or technical potential like as seen in the studies mentioned above. In addition, there has also been recent and increasing interest by policy makers and investors to have a visualization and knowledge of specific areas that would yield the optimum returns and consumer satisfaction. In this present study, both the techno-economic and evaluation of the sites have been analyzed to provide a more comprehensive insight into potential areas of interest for investment.

In Ghana, geospatial techno-economic and site assessments of the two selected solar energy technologies are still in their infancy and limited, not to mention an assessment for all regions. For instance, in a study by Agyekum and Velkin [62], the System Advisor Model (SAM) software was used to assess the techno-economic viability of CSP for only two selected towns in the northern part of Ghana. Their assessment was however only limited to CSP, two towns as well as the study did not consider an evaluation of the site to assess its viability for the CSP project. A review of the literature also show studies carried out by IRENA to estimate the potential of renewable energy in the entire Africa region in 2014 [63]. Results from IRENA' analysis show that, about 229 TWh/year of CSP and 7644 TWh/year of large-scale PV can be generated in Ghana based on their selected suitability criteria [63,64]. IRENA's assessment did not also factor in the economic viability of solar project. The concept of evaluating the techno-economic and site feasibility of solar energy potential using geospatial tools and software is still in its early stages. This makes the current study a maiden effort towards opening-up further discussions and studies on the development of solar energy markets and investment risks, even at more disaggregate levels. An assessment at disaggregate levels would also promote and encourage decentralization of electrification planning at the local levels.

Research objective

The main objective of this study is to ascertain the feasibility of utility-scale solar PV, and parabolic trough CSP systems penetration in Ghana by assessing the techno-economic and conduciveness of potential locations for the technology deployment. For this purpose, the geographical, the technical and the economic viability of utility-scale solar PV, and parabolic trough CSP systems have been evaluated using GIS and AHP multi-criteria methods.

Methodology

This chapter of the study provides detail description of the methods used and applicability using Ghana as a case study. In this study, the techno-economic potentials and site suitability for utility-scale solar PV and parabolic trough CSP technologies have been estimated. Despite the differences among the CSP technologies, the parabolic trough dominates the CSP markets and is the most commercially matured CSP technology [22].The analysis applied a combined geospatial multi-criteria method, i.e., applied GIS and the AHP multi-criteria analysis methods. The input datasets that were used for this study were all open-sourced and resampled to the same resolution to achieve uniformity in level of detail of study results. All datasets were interpolated to a $1km^2$ grid cell size and the two solar energy potentials were estimated and visualized for all 10 regions in Ghana. It must be mentioned that the site evaluation parameters and values used in this study were not only based on evidences from empirical studies in the Africa region [7,63] but also consideration was given to the national electrification policy of Ghana [58]. Hence, in the present paper, consideration for people living in close proximity to the grid network and with higher population densities were more suitable and assigned higher weights in constructing the pairwise comparison matrices.

Study area

Ghana is located in the western part of Africa at latitude 7.9465° N, and longitude of 1.0232° W. The country shares its borders with Togo to the east, Côte d'Ivoire to the west, Burkina Faso to the north, and to the south, lies the Atlantic Ocean and the Gulf of Guinea. Ghana covers an area of about 238,723 km^2. The terrain consists mostly of low plains with scattered hills and highlands. The highest point in Ghana, Mt. Afadjato which forms part of the Akwapim-Togo Ranges is ~885m above sea level [65]. The country is also home to the world's largest artificial lake by surface area (~8482 km^2): the Lake Volta [65]. The climate in Ghana is tropical: warm and humid with annual mean temperature ranging from about 26–29 °C [66]. Total population as at 2021 is about 31 million with average household size of 3.6 [67].

It is however important to mentioned that the regional boundaries used for this study were the former 10 regions of Ghana. This is due to the challenges in acquiring GIS administrative boundaries data for the recent 2018 referendum that led to the creation of 6 new regions from the former 10 regions [67,68] as shown in Figure 1.

Concept of the Analytic Hierarchy Process (AHP)

The AHP approach is a multi-criteria decision-making approach that uses hierarchical structures to illustrate a problem and help make judgement based on expert advice to deduce priority scale [30,55]. With AHP, combination of qualitative and quantitative inputs are allowed to help deal with complex problems in energy planning [23]. AHP is used to mitigate the uncertainty and inconsistencies that may arise in the evaluation process [23,29]. A consistency ratio (CR) must also be calculated to determine the degree of inconsistency in the judgment of decisions through the pairwise comparison process. Here all identified criteria are compared against each other in the pairwise comparison matrix and then numerical values are assigned to a criterion expressing judgement of relative importance of a criterion against another [30,69]. With the AHP method, a scale of comparison ranging from values of 1 to 9 is used to describe the intensity/ level of importance among the compared criteria, where the value of 1 is used to represent "equal importance" and 9 for criteria having "extreme importance" over the other criteria. Table 1 and Table 2 show the pairwise comparison matrix of the five major criteria used for this study which were derived from extensive review of literature to identify suitable areas for utility-scale solar PV and CSP systems in Ghana. To apply this method, first an unstructured problem must be disintegrated in hierarchical order, define the goal, and then identify the alternatives and criteria. Next, a pairwise comparison matrix **(A)** is constructed and $\boldsymbol{n}$ as the number of criteria. The matrix depicts the expert judgment of the pair-wise comparisons. Matrix **(A)** will then represent a matrix where each entry $\boldsymbol{a_{ij}}$ of the matrix defines the significance of the $\boldsymbol{i_{th}}$ criterion to the $\boldsymbol{j_{th}}$ criterion [23,30,52]. The below steps provide further insight into carrying out AHP for this study:

$$A = \begin{bmatrix} 1 & a & b \\ 1/a & 1 & c \\ 1/b & 1/c & 1 \end{bmatrix} \quad (1)$$

After computing the pairwise comparison matrix, the next step is to check for the consistency of the matrix. As mentioned earlier, even though the values assigned to criteria are based on expert opinions and experiences and not set arbitrarily, it is still important to determine the level of inconsistencies in the matrix as people' decisions and preferences are sometimes intransitive and inconsistent, and this may cause perturbations in computing the eigenvector of a criteria [69]. Hence, the next step of the AHP

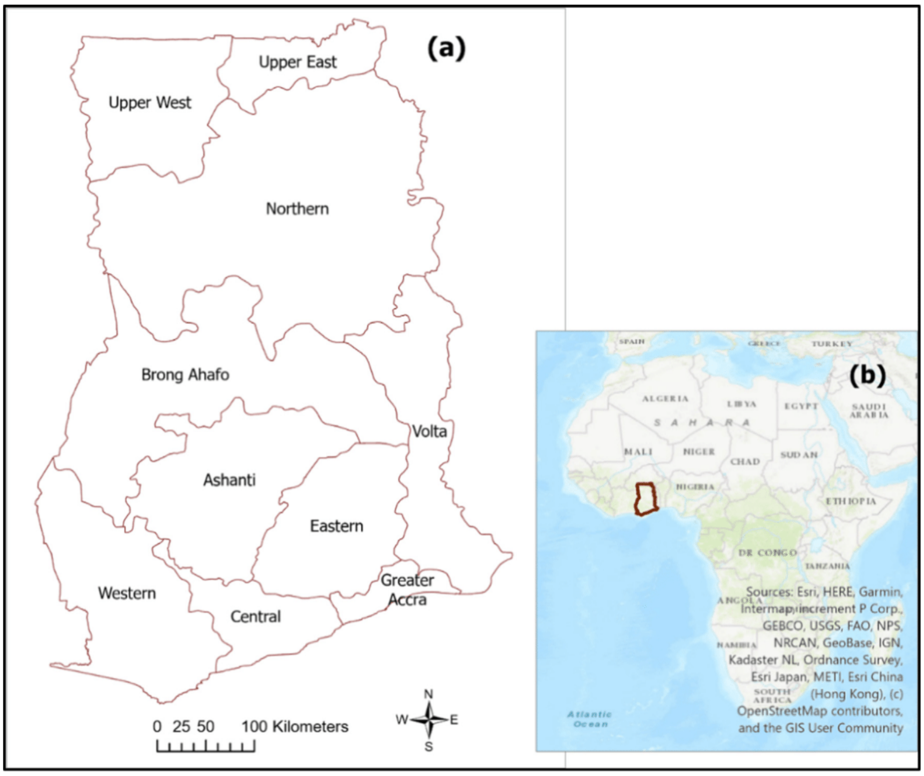


Figure 1. Map of Ghana with the 10 regions. (a) Map of Ghana, (b) Geographical location of Ghana.

Table 1
Pairwise comparison matrix for the utility-scale PV system.

Criteria	Slope	Population Density	Distance to major roads	Solar Irradiance (GHI)	Distance to Electricity Grid Network
Slope	1.00	0.33	0.20	0.13	0.11
Population Density	3.00	1.00	0.33	0.20	0.11
Distance to major roads	5.00	3.00	1.00	0.25	0.13
Solar Irradiance (GHI)	8.00	5.00	4.00	1.00	0.50
Distance to Electricity Grid Network	9.00	9.00	8.00	2.00	1.00

Table 2
Pairwise comparison matrix for the CSP system.

Criteria	Slope	Distance to Rivers	Distance to Electricity Grid Network	Population Density	Solar Irradiance (DNI)
Slope	1.00	0.50	0.50	0.33	0.20
Distance to Rivers	2.00	1.00	0.33	0.50	0.33
Distance to Electricity Grid Network	2.00	3.00	1.00	0.50	0.50
Population Density	3.00	2.00	2.00	1.00	0.50
Solar Irradiance (DNI)	5.00	3.00	2.00	2.00	1.00

Table 3
Values for **RI**.

n	2	3	4	5	6	7	8	9
RI	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45

method is to calculate the consistency ratio **CR** which is defined as the ratio of the consistency index **CI** to the average consistency index **RI**[1]. **CR** is thus given as [30]:

$$CR = \frac{CI}{RI} \quad (2)$$

The value of **RI** is based on the average of consistency of square matrices of number of observed criteria ***n*** with its corresponding assigned **RI** value. Table 3 shows the **RI** value of the given number of observations ***n*** as proposed by Thomas L. Saaty [30].

Next is to compute the consistency index **CI** which is given as [30]:

$$CI = \frac{\lambda_{max-n}}{n-1} \quad (3)$$

If the value for **CR** is < 0.1, then the degree of consistency is acceptable otherwise, decision judgment is inconsistent and based on experiences and expert opinions Saaty [30,70] recommended a revision of the preference pairwise matrix if **CR** > 0.1. Computation of criteria weights resulting from the pairwise matrices for the 2 selected solar energy technologies are shown in Table 4 and Table 5.

Area suitability criteria: Input raster layers

This section highlights all the input variables or decision criteria that were considered in this study for selecting optimal sites for solar energy projects in Ghana (see Figure 2**)**. All input layers were rasterized and reclassified into 5 classes and level of importance was assigned to areas from a scale of 1 to 5, with 1 having the highest prominence.

(a) Solar Irradiance

The first question that generally comes to mind when considering solar energy project is if the location receives enough solar irradiance worth harnessing for electricity. It is one of the main necessary criteria that should be available to determine the suitability of a site for the installation of a solar technology [7,23,29,43,44,52,54–56,63,64,69,71–74]. Solar radiation datasets for both the Global Horizontal Irradiance (GHI) and the Direct Normal Irradiance (DNI) were openly-sourced from the Global Solar Atlas (GSA) portal [75]. From the nearest resample technique used, GHI values in Ghana ranges from 1 500 kWh/m^2/year to 2 080 kWh/m^2/year which makes the solar irradiance intensity in Ghana very viable for utility-scale PV system, as well as for residential or a distributed electrification system. The DNI intensity index in Ghana on the other hand is rather nominal; ranging from 700 kWh/m^2/year to 1 450 kWh/m^2/year which makes CSP-based electrification in Ghana more conducive for micro-grids or distributed systems rather than for large-scale CSP projects.

(b) Slope

The gradient of the topography of the selected site can greatly affect the amount of solar radiation received by the site. The landscape must usually not tilt more than 100% (45°) for PV systems [63,64] and less the 3.7% (2.1°) [63,64] for CSP systems to ensure optimal reception of the solar radiation. Hence prominence was given to areas with lower slope. The slope dataset was accessed from the Land Use Change and Agriculture Program, International Institute for Applied Systems Analysis portal [76].

(c) Population Density

The number of persons per km^2 of the site is an important factor to consider in determining the optimal technology solution to assign. This particularly helps to identify where demand is to offer best-least cost solutions. The population density dataset used was extracted from the 2020 Africa population by WorldPop [77] in a tiff format. The downloaded data was for the entire Africa continent and the *extract by mask* tool in ArcGIS was used to extract that of Ghana. Areas with higher population densities with given higher prominence.

(d) Grid Infrastructure

As the name suggests, proximity to the power grid plays an integral role in especially assigning an electrification solution to the end-user. It therefore importance to site the solar plant in areas with existing or proposed transmission and distribution networks. This is also to ensure that there is enough demand to meet the energy generated and to offer optimal cost-effective solutions.

[1] The average consistency index **RI** is also referred to as the random index [70].

Table 4
Criteria weights for the utility-scale solar PV system.

Criteria	Slope	Population Density	Distance to major roads	Solar Irradiance (GHI)	Distance to Electricity Grid Network	**Weights (%)**
Slope	0.04	0.02	0.01	0.03	0.06	**3.33**
Population Density	0.12	0.05	0.02	0.06	0.06	**6.21**
Distance to major roads	0.19	0.16	0.07	0.07	0.07	**11.35**
Solar Irradiance (GHI)	0.31	0.27	0.30	0.28	0.27	**28.53**
Distance to Electricity Grid Network	0.35	0.49	0.59	0.56	0.54	**50.58**

Here, **CI** = 0.076 **CR** = 0.068

Table 5
Criteria weights for the CSP system.

Criteria	Slope	Distance to Rivers	Distance to Electricity Grid Network	Population Density	Solar Irradiance (DNI)	**Weights (%)**
Slope	0.08	0.05	0.09	0.08	0.08	**7.42**
Distance to Rivers	0.15	0.11	0.06	0.12	0.13	**11.26**
Distance to Electricity Grid Network	0.15	0.32	0.17	0.12	0.20	**19.08**
Population Density	0.23	0.21	0.34	0.23	0.20	**24.25**
Solar Irradiance (DNI)	0.38	0.32	0.34	0.46	0.39	**37.99**

Here, **CI** = 0.039 **CR** = 0.034

Also, the further the grid network, the more expensive the LCOE, since the transmission network will have to be extended to the generation point and to where demand is located, thereby increasing overall costs of production. The grid infrastructure dataset was accessed from the World Bank data catalogue portal [78].

(e) Road Network

Conventionally, the location of a solar plant must be easily accessible [52] to allow for easy access during all the development phases; from preliminary site evaluation, plant installation, transmission and for maintenance purposes. Access to road infrastructure goes a long way to help minimize investment costs [7,49,50,79], especially cost associated with transportation. It is therefore of an economic and technical relevance to consider proximity to road infrastructure in evaluating suitable sites for solar electrification projects. In addition, it is expected that, people are more likely to live in areas where they could have access to transport and therefore important to include proximity to road infrastructure in identifying suitable locations for siting a solar plant. Road proximity evaluation also helps to avoid the oversight of installing the power plant in areas designated for road construction. Areas closer to roads were more preferred and assigned higher score of importance.

(f) Rivers

Availability of water is an important factor to consider especially for CSP systems. Therefore, the closer the power plant is to a water body, the more convenient. Just like many conventional thermal power plants, most CSP installations need water to cool and condense the steam cycle [22]. The chosen CSP technology selected must be regularly cleaned off dust that settles on the mirrors to ensure sufficient reception of the solar insolation [80–82]. Hence, areas closer to water bodies were considered more suitable for siting a CSP plant. It must be mentioned that availability of this criterion was only considered for CSP systems. The river dataset was accessed from the World Bank data catalogue portal [83].

(g) Area Restriction Mask

In this study, for ecological and environmental protection reasons, delimited areas like international protected areas were completely excluded from all the solar project site selection as it is not advisable to install power plants in protected areas [53,84]. Protected areas are one of the major restricted areas considered in this study and they include areas like wetlands, Ramsar sites, forest reserves, parks, etc. The protected areas dataset was openly accessed at UNEP-WCMC and IUCN [85].

Estimation of the geographical potential

The geographical potential refers evaluation of sites for development of the 2 solar technologies. The topography of Ghana's terrain must fulfil certain necessary and minimum environmental conditions to ascertain the viability of installing a solar PV or CSP plant on a site to ensure optimal energy generation and deployment. The evaluation of the geographical potential included expert advice on site selection criteria that the location must meet to be suited for building utility-scale solar PV or CSP system. To analyze this, the AHP method was used to assign weights of importance to selected criteria, such as the slope of the terrain, population density of the location, proximity to power grid infrastructure, distance to road network, etc.

After the criteria selection, the next step was to identify, estimate and exclude all restricted areas from the suitable area. The Boolean binary method in the GIS environment was used to exclude all protected areas which forms the area restriction mask from the analysis. Thus, all areas that either did not meet the minimum suitable criteria or are protected were assigned the value *0* and the remaining suitable areas were assigned the value of *1*. And this is the first reduction in the potential estimation of the solar PV and CSP energy output because part of the overall land area is reduced due to the exclusion mask.

Further, the remaining suitable land areas were subjected to suitability criteria. All identified suitable criteria were reclassified and assigned weights to identify areas that were either excellent or poor for the installation of each solar technology. As mentioned, the AHP was used to assign weights to all the suitable criteria of the site. The AHP is one of the most common and widely used approach and it consists of grouping criteria into a square matrix and performing a pair-wise comparison to place level and scale of importance on each suitable criterion. Based on the pair-wise matrix, a general percentage score was computed and assigned to each criterion which is also reflective of the level of importance assigned to the criteria. For this study, 5 suitability criteria were used and then based on level of importance or prioritization, were reclassified into 5 classes with class 1 being identifies as (excellent) location, class 2 (very good), class 3 (good), class 4 (moderate), and class 5 (poor). The geographical potential maps for both technologies are shown in Figure 3.

Estimation of the technical potential

After identification of suitable locations for the solar PV and CSP systems is the estimation of the technical potential. The technical potential basically refers to the amount of electric energy that can be generated given the geographical potential by the selected solar technology over an estimated period of time. In this study, the maximum energy output per grid cell is estimated per year (GWh/year), see Figure 4. Basic methods have been proposed in many studies to estimate the technical potential or electrical potential of solar PV and CSP systems of a location [7,63,74,86,87]. For this study, the equation used by IRENA [22,63,64] and Yushchenko et al. [7] was adopted and it is given as:

$$E_i = \mathrm{GHI}_i(\text{or } \mathrm{DNI}_i) * \mathrm{Efficiency} * \mathrm{PR}_{\text{pv (for PV systems)}} * \left[\frac{AvailArea_i}{SpacingFactor}\right] \quad (4)$$

Where, E_i refers to the technical solar energy potential to be generated per year (GWh/y), (i) represents the grid cell value per km^2. GHI and DNI are the solar irradiation values of the location for either PV or CSP system, respectively. $\mathrm{PR}_{\text{pv (for PV systems)}}$ was only included in estimating the technical energy output for the solar PV technology. $AvailArea_i$ represents the geographical potential (suitable areas) and the *spacingfactor* is the ratio of total land requirements to the surface of the solar panels or CSP collectors [7]. *Efficiency* as used here refers to the module efficiency for the PV or the CSP technology while PR_{pv} is the performance ratio of the PV module. The selected module specifications are based on expert advice from reviewed literature [7,63,74,86,87]. The module specification assumptions used in this study for the 2 selected solar energy technologies is shown in Table 6.

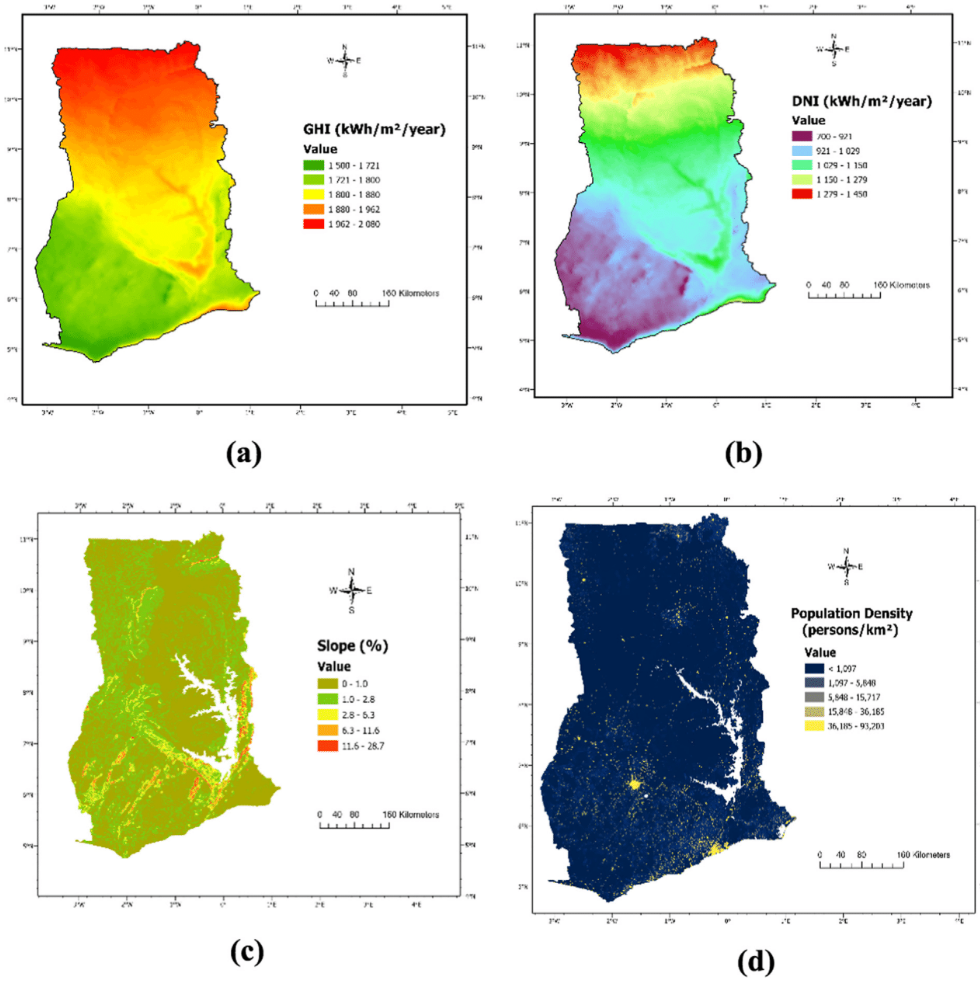


Figure 2. Input raster data for computing geographical potential. (a): Global Horizontal Irradiance, (b): Direct Normal Irradiance, (c): Slope, (d): Population Density, (e): Grid Network, (f): Roads, (g): Rivers, (h): Area restriction mask.

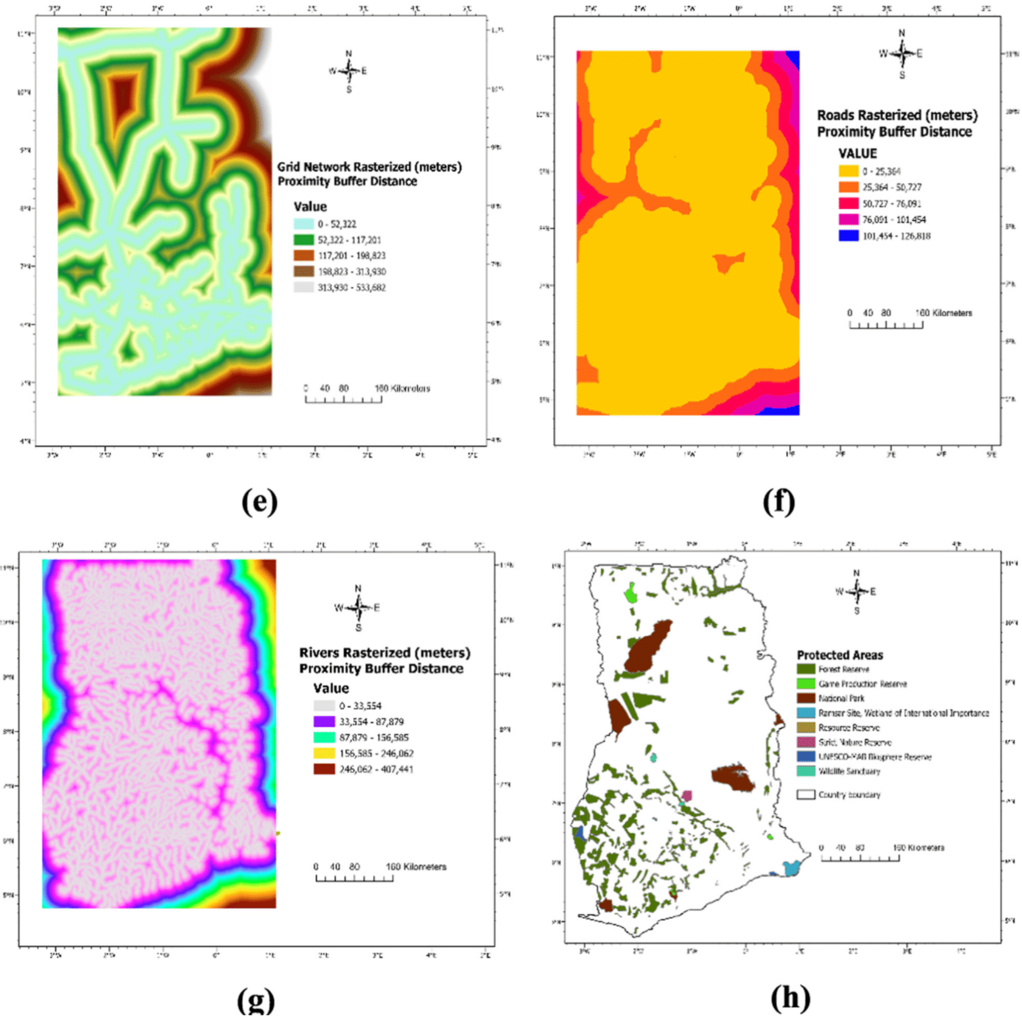


Fig. 2 (*continued*)

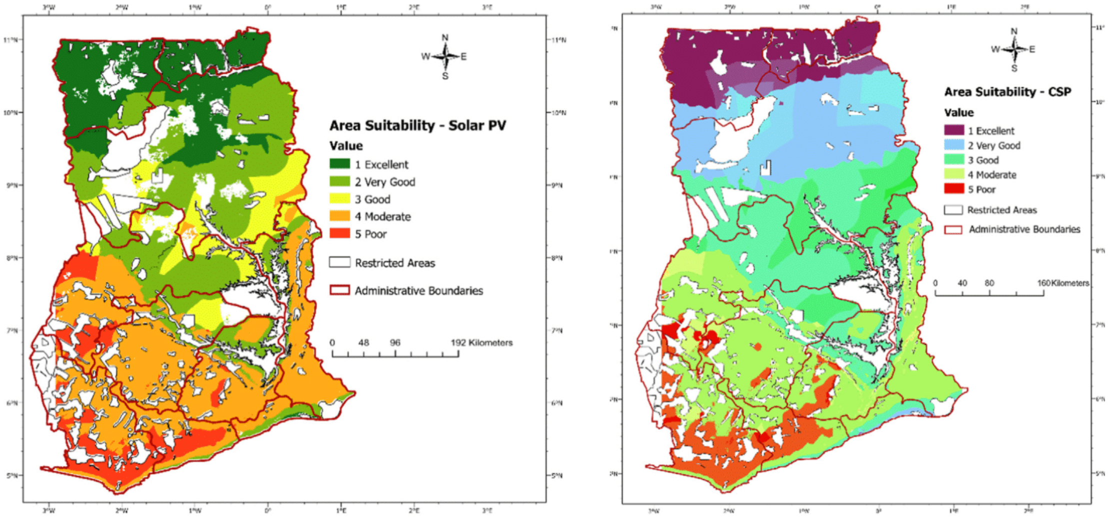
Estimation of the economic potential

The economic potential is evaluated by estimating the LCOE for utility-scale solar PV and CSP systems. As mentioned, the LCOE is used as a measure to compare the lifetime costs of generating electricity from different generation technologies [59,88,89] which includes components like the initial capital costs, operations and maintenance costs (O&M), discount rate, etc. Just like the technical potential, the LCOE is estimated based on the energy output generated per grid cell, i.e., km^2. The formula used for estimating the LCOE of the solar energy technologies is given as [17,61,90]:

$$LCOE_i = \left[\sum_{t=1}^{n} \frac{I_{ti} + M_{ti}}{(1+r_i)^t}\right] \Big/ \left[\sum_{t=1}^{n} \frac{E_{ti}}{(1+r_i)^t}\right] \quad (5)$$

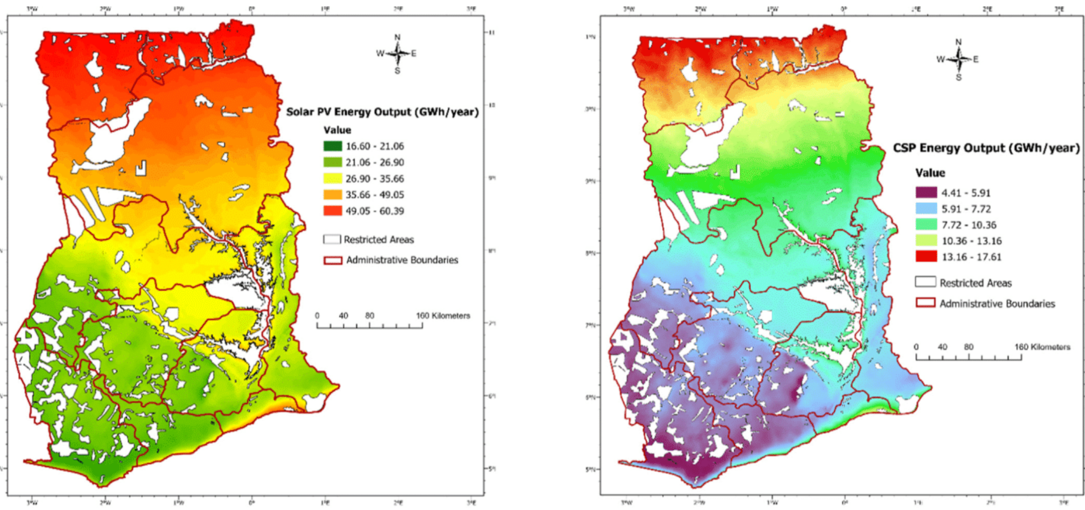
Where: $LCOE_i$ refers to the average lifetime levelized cost of electricity generation per grid cell, I_{ti} is initial capital costs in the year t per grid cell, M_{ti} is the O&M costs in the year t per grid cell, E_{ti} is the energy generated in the year t per cell, r_i is discount rate per cell and n represents the lifetime of the system.

The metrics used in this analysis are further elaborated in IRENA's renewable power generation costs in 2020 report [61]. It must however be mentioned that to estimate the LCOE per cell, all the costs component remained constant across grid cells except for the energy outputs that were the only variables. As projected in the report, initial capital costs of installed capacity per cell for utility-scale PV and CSP were $883/kW and $4581/kW, respectively. A 10% rate for both PV and CSP was used to estimate the O&M costs and at a discount rate of 7.5% for both technologies over a lifetime period of 25 years. The LCOE values were calculated and imported into the GIS environment to create visualisations of the economic potential maps (see Figure 7). It also important to emphasise that due to the evolving markets for the solar technologies, the LCOE results obtained in previous and subsequent years may differ due to variations in the costs components used in the estimations. For this assessment and as already stated, the cost val-



(a) (b)

Figure 3. Area suitability Maps. (a) Area suitability for solar PV deployment, (b) Area suitability for CSP deployment.



(a) (b)

Figure 4. Maps showing maximum energy generation capacity per year per grid cell (GWh/year). (a) Utility-scale solar PV energy output, (b) CSP energy output.

Table 6
Solar PV and CSP technology specifications and assumptions used in estimating the technical solar energy potentials.

Specification	Utility-scale PV system	CSP system
Technology	Monocrystalline cells	Parabolic trough
Efficiency	Module efficiency 15–22%, PR 70–85%	System efficiency15–21%
Spacing factor	1.4–5	3–7.5

ues used were obtained from IRENA's report due to limited data availability at the country level.

Results

In this section, results of the two energy potential categories for utility-scale solar PV and CSP technologies have been highlighted and explained. This includes results from estimation of the geographical potential, the technical potential, and the economic potential for utility-scale solar PV and CSP at the national level and within the 10 regional boundaries in Ghana. Figure 5 and

Figure 6 show the geospatial models used to estimate the geographical and technical potentials, respectively. As mentioned earlier, the overarching purpose of this study is to help energy policy makers in Ghana make better decisions in their sustainable energy access planning and RE integration initiatives, and more importantly to encourage decentralization of energy access interventions at the local government level (regional level).

Geographical potential

This section provides insights into the outcome of the analysis of this study which includes site evaluation of suitable areas for development of the 2 selected solar energy technologies. From the dataset used [91], Ghana has a total land area of about 238,723 km^2 and about 203,795 km^2 (85%) area of the land is suitable for both utility-scale solar PV and CSP development. Total restricted area is about 34,928 km^2. Site evaluation for the 10 regions in Ghana show varying geographical potential with Northern region having the largest suitable land area (30%) for the development of both solar technologies in Ghana and with the Greater Accra region having the smallest available land (2%). Table 7 and Table 8 show the various percentage share of actual land area and suitable area both at the regional and national levels in Ghana for the two technologies

Site evaluations show varying geographical potentials across the regions in Ghana. At the regional level, the Upper West region shows the area with the highest generation capacity of about 56% (class 1), and least with potential share of 0.14% in the Greater Accra and the Volta regions for utility-scale solar PV. Nationally, about 51% (classes 1- 3) of total land area in Ghana is very ideal for development of utility-scale PV solution and only about 8% (class 5) of suitable areas show poor potential for utility-scale solar PV, see Table 7.

Also, despite the nominal DNI intensity in Ghana, suitable areas for CSP system however show great potential as shown in Table 8. For instance, about 62% (classes 1-3) of suitable areas in Ghana show promising potentials. Only about 9% (class 5) of suitable areas show poor potential, with the Volta region having the poorest technical potential per suitable area of about 0.14%. The Upper West region still has the largest CSP technical potential per suitable areas of about 56% (in class 1). See Figure 3 for geospatial suitability maps for the 2 selected technologies under research.

Technical potential

In this section, results from the technical estimation of the annual energy output generated by the 2 selected solar energy technologies have been explained. As mentioned earlier, the technical potential here refers to the amount of solar energy that the utility-scale solar PV and CSP systems can generate annually given the geographical potentials or suitable areas. It must be emphasized that, the energy output visualized in Figure 4 are based on a grid cell values where the maximum value per grid cell was used to estimate the technical potential of the location in GWh/year. But for the total capacity generated per region and nationally, sum of all grid cell values within a region was used i.e., in TWh/year.

Results of the analysis show that, a total of ~68,622 TWh/year of solar energy can be generated annually from utility-scale PV sys-

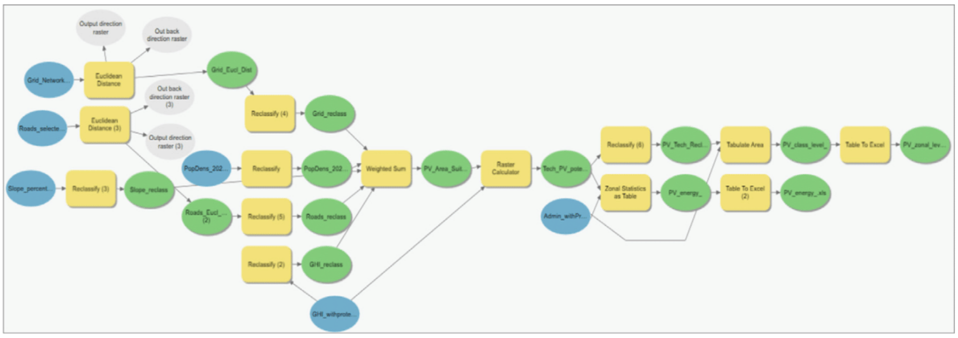


Figure 5. Geographical and technical potential estimation model for the utility-scale PV system.

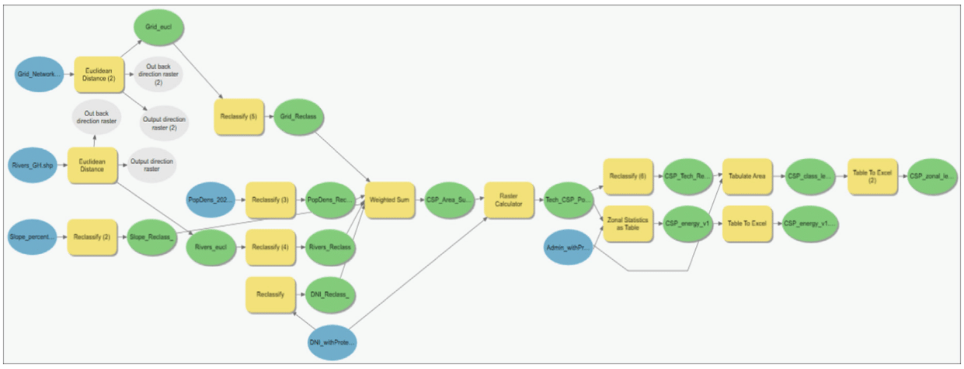


Figure 6. Geographical and technical potential estimation model for the CSP system.

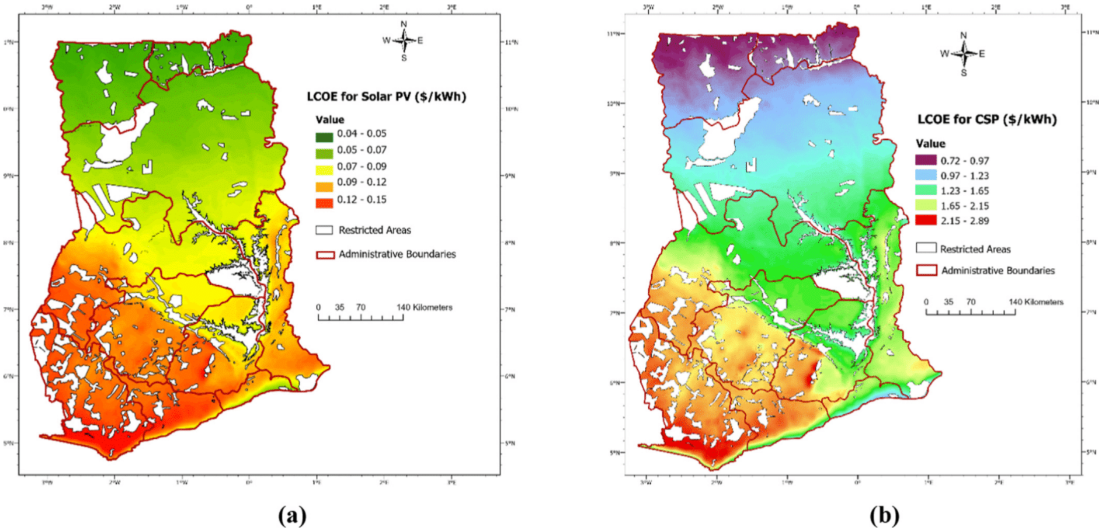


Figure 7. Maps showing the LCOE estimates per grid cell for both solar technologies. (a) LCOE estimates for Utility-scale solar PV system, (b) LCOE estimates for CSP system.

Table 7
Share of utility-scale solar PV technical potential per suitability class (%).

Region	Class	1 (Excellent)	2 (Very Good)	3 (Good)	4 (Moderate)	5 (Poor)
Ashanti		–	–	5.76%	21.07%	4.84%
Brong Ahafo		–	–	22.78%	17.30%	24.48%
Central		–	–	0.71%	6.79%	21.84%
Eastern		–	–	4.99%	14.73%	4.30%
Greater Accra		–	0.91%	2.35%	2.46%	0.14%
Northern		10.39%	68.51%	56.42%	9.74%	–
Upper East		33.27%	5.71%	–	–	–
Upper West		56.33%	24.85%	2.44%	–	–
Volta		–	0.02%	4.55%	17.36%	0.14%
Western		–	–	0.01%	10.55%	44.27%
Total		**10.13%**	**10.11%**	**30.78%**	**41.08%**	**7.89%**

Table 8
Share of CSP technical potential per suitability class (%).

Region	Class	1 (Excellent)	2 (Very Good)	3 (Good)	4 (Moderate)	5 (Poor)
Ashanti		–	–	10.38%	24.81%	6.07%
Brong Ahafo		–	–	31.60%	20.34%	6.87%
Central		–	–	0.90%	8.05%	21.72%
Eastern		–	–	6.94%	15.15%	11.01%
Greater Accra		0.01%	1.39%	2.44%	2.77%	–
Northern		16.43%	89.96%	38.89%	–	–
Upper East		28.06%	–	–	–	–
Upper West		55.50%	8.49%	–	–	–
Volta		–	0.16%	8.80%	18.46%	0.04%
Western		–	–	0.06%	10.41%	54.28%
Total		**13.30%**	**19.46%**	**28.97%**	**29.53%**	**8.74%**

tem in Ghana, see Table 9. Regionally, the Northern region generated the highest utility-scale PV energy with capacity of about 22, 203 TWh/year with a national geographical potential share of 30%, followed by the Upper West region with a technical potential of about 10,517 TWh/year with a national geographical potential share of 9%. The Greater Accra region at the national level, generated the lowest technical potential of about 1079 TWh/year given its geographical potential of 2%. At the regional level however, the Western region generated the lowest maximum capacity of ~ 28.83 GWh/year, followed by the Ashanti region with maximum capacity per grid cell of ~ 30.11 GWh/year. The CSP system generated an annual capacity of about 23,453 TWh/year in Ghana. Again, under the criteria and assumptions used for this study, the Northern region showed the highest annual generation capacity of ~8560 TWh/year. The Greater Accra and the Central regions showed the lowest annual CSP potential of ~377 TWh/year and ~685 TWh/year, respectively, see Table 10.

Economic potential

In this study, the LCOE approach was used to estimate the economic potential for utility-scale solar PV and CSP technologies for Ghana. This approach was used to provide insights and estimation of the costs involved in the generation and integration per unit of

Table 9
Geographical, Technical and Economic potential of utility-scale solar PV system for Ghana.

Region	Actual Land Area (km^2)	Suitable Area (km^2)	National share of suitable area (%)	Share of suitable area within region (%)	PV $Energy_{Min}$ (GWh/year)	PV $Energy_{Max}$ (GWh/year)	PV $Energy_{Mean}$ (GWh/year)	PV $Energy_{Total}$ (TWh/year)	PV $LCOE_{Max}$ ($/kWh)	PV $LCOE_{Min}$ ($/kWh)	PV $LCOE_{Mean}$ ($/kWh)
Ashanti	24,793	20,847	10.23%	84.08%	16.90	30.11	24.12	5792.16	0.1452	0.0815	0.1018
Brong Ahafo	39,670	32,626	16.01%	82.24%	16.60	30.74	25.88	9225.66	0.1478	0.0798	0.0948
Central	9655	8777	4.31%	90.91%	17.04	29.95	21.37	2244.00	0.1440	0.0819	0.1148
Eastern	18,661	17,206	8.44%	92.21%	17.14	30.74	24.04	4232.59	0.1432	0.0798	0.1021
Greater Accra	3671	3543	1.74%	96.51%	18.66	40.73	26.45	1078.86	0.1315	0.0603	0.0928
Northern	69,037	60,238	29.56%	87.25%	23.53	58.94	34.06	22203.45	0.1043	0.0416	0.0721
Upper East	8665	7369	3.62%	85.04%	47.29	60.10	57.77	5067.24	0.0519	0.0408	0.0425
Upper West	19,466	17,370	8.52%	89.23%	30.59	60.39	52.77	10516.61	0.0802	0.0406	0.0465
Volta	20,467	18,847	9.25%	92.08%	18.11	40.11	24.58	4664.48	0.1355	0.0612	0.0998
Western	24,639	16,972	8.33%	68.88%	16.90	28.83	20.68	3597.14	0.1452	0.0851	0.1187
Total	**238,723**	**203,795**	**100%**	**85%**				**68622.18**			

Table 10
Geographical, Technical and Economic potential of CSP system for Ghana.

Region	Actual Land Area (km^2)	Suitable Area (km^2)	National share of suitable area (%)	Share of suitable area within region (%)	CSP $Energy_{Min}$ (GWh/year)	CSP $Energy_{Max}$ (GWh/year)	CSP $Energy_{Mean}$ (GWh/year)	CSP $Energy_{Total}$ (TWh/year)	CSP $LCOE_{Max}$ ($/kWh)	CSP $LCOE_{Min}$ ($/kWh)	CSP $LCOE_{Mean}$ ($/kWh)
Ashanti	24,793	20,847	10.23%	84.08%	4.92	9.08	7.00	1879.54	2.5879	1.4023	1.8189
Brong Ahafo	39,670	32,626	16.01%	82.24%	5.08	9.67	7.83	3050.29	2.5064	1.3167	1.6261
Central	9655	8777	4.31%	90.91%	5.12	11.53	6.11	685.18	2.4868	1.1043	2.0839
Eastern	18,661	17,206	8.44%	92.21%	4.41	9.67	7.07	1300.66	2.8872	1.3167	1.8009
Greater Accra	3671	3543	1.74%	96.51%	5.23	14.79	8.49	376.77	2.4345	0.8609	1.4997
Northern	69,037	60,238	29.56%	87.25%	7.36	16.40	11.19	8559.79	1.7300	0.7764	1.1379
Upper East	8665	7369	3.62%	85.04%	12.73	17.25	16.49	1520.68	1.0002	0.7381	0.7721
Upper West	19,466	17,370	8.52%	89.23%	11.47	17.61	15.63	3488.14	1.1101	0.7230	0.8146
Volta	20,467	18,847	9.25%	92.08%	4.58	12.22	7.51	1491.73	2.7800	1.0419	1.6954
Western	24,639	16,972	8.33%	68.88%	4.68	10.53	5.68	1099.85	2.7206	1.2092	2.2417
Total	**238,723**	**203,795**	**100%**	**85.37%**				**23452.64**			

solar energy generated by the technology. As mentioned earlier, the entire study is based on a grid cell assessment and hence the maximum values as shown on the map represents the potential LCOE estimate of the maximum energy output generated within the grid cell, i.e., per km^2 as visualized on the maps in Figure 7.

The LCOE for a CSP technology in Ghana is much more expensive than for the utility-scale solar PV, see Table 9 and Table 10. For example, in the Upper West; the region with the largest generation capacities for both technologies, the maximum energy generated by the PV system i.e., 60.36 GWh has LCOE of $0.04/kWh while that of the CSP system with maximum capacity of about 17.16 GWh has unit cost or LCOE of $0.72/kWh. From the study and as shown on the maps in Figure 7, the LCOE for the utility-scale solar PV technology ranges from about $0.04/kWh to $0.15/kWh, and from a minimum of $0.73/kWh to a maximum of $2.89/kWh for a CSP technology in Ghana.

Discussion

In this study, a combined geospatial-AHP multicriteria decision methods were applied to the case of Ghana to estimate the geographical, technical, and economic viability of utility-scale solar PV and CSP systems in the country. The GIS Boolean method was applied as the first step to delimit and delineate suitable areas from the restricted areas. Areas that were classified as restricted or delimited such as protected areas were completely excluded from the analysis. The suitability area criteria were based on extensive review of literature [7,37,43,63,64,72,74,84], etc. It must however be stated that, even though similarities exist between criteria selections, value thresholds differ slightly based on technology assumptions, geographical location, and objective of the solar project. The analysis was carried out at a grid cell resolution of $1km^2$ per land area. The AHP [30] which is most widely used and the WSA multi-criteria methods were used in the ArcGIS environment to compute the geographical and technical potentials of the solar technologies used. The values for the LCOE were however computed in excel and then imported into the GIS environment. This study is particularly relevant to Ghana's decarbonization agenda. Further, a review of the literature shows limited geospatial solar energy potential assessment in Ghana to assist policymakers make informed decisions. The only similar studies that have been carried out were done by IRENA for the Africa and the ECOWAS region [17,61,63,64] and technical potential for countries in West Africa by Yushchenko et al. [7] and not specifically on Ghana and hence the level of detail is not comparable. Results of this assessment show varying potentials for the 2 selected solar technologies, with total generation capacities of ~68,622 TWh for a utility-scale solar PV technology and ~23,453TWh for the CSP technology. The LCOE for the utility-scale solar PV technology ranges from a minimum of about $0.04/kWh to a maximum of $0.15/kWh, and from ~ $0.73/kWh to ~$2.89/kWh for the CSP technology in Ghana. The LCOE estimations are comparable as they fall within values obtained in other studies like that of [62]. Evidence from other countries have also shown that where there are right regulatory and policy frameworks in place, access to low-cost finance is available [92].

Conclusion

The techno-economic potential and site viability for utility-scale solar PV and CSP system for Ghana have been evaluated. Out of the about 238,723 km^2 of Ghana's land areas, about 203,795 km^2 (85%) available land is suitable for solar energy development. In addition, ~68,622 TWh/year of energy from utility-scale PV can be deployed annually in Ghana, and ~23,453 TWh/year from the CSP technology. The economic potential (LCOE) for the utility-scale solar PV technology ranges from about $0.04/kWh to $0.15/kWh, and from about $0.73/kWh to $2.89/kWh for the CSP technology in Ghana. Also as already discussed, there are various factors that accounted for the unit cost of each technology. For Ghana, aside the evolving markets for the solar technologies, the overall capital costs, the O&M costs, and present discount rate, another major reason for the higher unit cost especially for the CSP technology is the low DNI intensity in the country.

Further studies are however needed to analyze the implementation potential for the selected solar technologies to understand the feasibility of implementing these projects given institutional constraints and incentives as evidence have shown that access to low-cost finance exist when the right policy framework is in place. In addition, an assessment of how to strengthen grid network connectivity to increase the uptake of solar energy would be valuable to reduce transmission and distribution losses.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

I would like to thank this journal and its anonymous reviewers for peer-reviewing this paper. Special thanks to my academic supervisors. I am also grateful to family and friends for their continuous support and encouragement.

References

[1] Energy Commission of Ghana, Ghana – Action Plan for Sustainable Energy for All by 2030.: SE4ALL-GHANA ACTION PLAN, 2012.
[2] World Bank, Beyond-Connections-Introducing-Multi-Tier-Framework-for-Tracking-Energy-Access-1.
[3] World Bank, Tracking sdg7 the energy progress report full_report, 2018.
[4] U. N. S. Division, — *SDG Indicators.* [Online]. Available: https://unstats.un.org/sdgs/report/2020/goal-07/ (accessed: Jun. 14 2021).
[5] World Bank, Sustainable Energy for All (SE4ALL), *Access to electricity (% of population) - Ghana | Data.* [Online]. Available: https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS?locations=GH (accessed: Jun. 14 2021).
[6] N.C. Lee, V. Leal, Renew. Sustain. Energy Rev. 31 (2014) 202–220, https://doi.org/10.1016/j.rser.2013.11.044.
[7] A. Yushchenko, A. de Bono, B. Chatenoux, M. Kumar Patel, N. Ray, Renew. Sustain. Energy Rev. 81 (2018) 2088–2103, https://doi.org/10.1016/j.rser.2017.06.021.
[8] IEA, *IEA Energy Atlas.* [Online]. Available: http://energyatlas.iea.org/#!/tellmap/-1118783123/1 (accessed: Jun. 14 2021).
[9] F.S. Javadi et al., Renew. Sustain. Energy Rev. 19 (2013) 402–416, https://doi.org/10.1016/j.rser.2012.11.053.
[10] M.G. Pereira, M.A.V. Freitas, N.F. da Silva, Renew. Sustain. Energy Rev. 14 (4) (2010) 1229–1240, https://doi.org/10.1016/j.rser.2009.12.013.
[11] A. Beltran, L. Laborie, P. Lanthier, S. Le Gallic (Eds.), *The Akosombo Dam and the Quest for Rural Electrification in Ghana: Creations, circulations, tensions, transitions (19th-21th C.) / Alain Beltran, Léonard Laborie, Pierre Lanthier, Stéphanie Le Gallic (eds.).* Bruxelles: P.I.E. Peter Lang, 2016. Accessed: Jun. 14 2021. [Online]. Available: https://www.peterlang.com/view/product/62126?format=PBK.
[12] International Hydropower Association (iha), *Ghana - International Hydropower Association.* [Online]. Available: https://www.hydropower.org/country-profiles/ghana (accessed: Jun. 14 2021).
[13] Energy Commission of Ghana, 2020 ENERGY (SUPPLY AND DEMAND) OUTLOOK FOR GHANA, [Online]. Available: http://www.energycom.gov.gh/planning/data-center/energy-outlook-for-ghana.
[14] Energy Commission of Ghana, 2018 Energy (Supply and Demand) Outlook for Ghana, 2018.
[15] Energy Commission Of Ghana (EC), "National Energy Statistics 2007 - 2016," Apr. 2017.
[16] IRENA & the German Federal Minister for Economic Cooperation and Development, The Renewable Energy Transition in Africa: Powering Access, Resilience and Prosperity, Mar. 2021.
[17] IRENA, Renewable Power Generation Costs in 2019, 2019.
[18] J. Hernández-Moro, J.M. Martínez-Duart, *Analytical model for solar PV and CSP electricity costs: Present LCOE values and their future evolution*, 2013. [Online]. Available: https://reader.elsevier.com/reader/sd/pii/S136403211200696X?

token=19A7A04F1FBA09003DC340EFBCAFD7BB0D569B3645E2C4C164189D1B65A203FE507BB055A16155B0660456B1980C404F&originRegion=eu-west-1&originCreation=20220317131847.
[19] Ministry of Energy, Energy Sector Recovery Program, May. 2019. [Online]. Available: http://energycom.gov.gh/files/2019%201111%20ESRP%20ESTF_Clean_v3.0redacted%20final.pdf.
[20] Ministry of Finance, Annual report on the management of the energy sector levies and accounts for 2019, [Online]. Available: https://mofep.gov.gh/sites/default/files/reports/economic/2019_Annual_ELSA_Report.pdf.
[21] A.-A. Mary, Energy 225 (2021) 120217, https://doi.org/10.1016/j.energy.2021.120217.
[22] International Renewable Energy Agency (IRENA), IRENA-IEA-ETSAP Technology Brief 1: Concentrating Solar Power (CSP), 2013.
[23] H.Z. Al Garni, A. Awasthi, Appl. Energy 206 (2017) 1225–1240, https://doi.org/10.1016/j.apenergy.2017.10.024.
[24] IRENA, Ghana Renewables Readiness Assessment.
[25] S. Freitas, C. Catita, P. Redweik, M.C. Brito, Renew. Sustain. Energy Rev. 41 (2015) 915–931, https://doi.org/10.1016/j.rser.2014.08.060.
[26] S.D. Pohekar, M. Ramachandran, Renew. Sustain. Energy Rev. 8 (4) (2004) 365–381, https://doi.org/10.1016/j.rser.2003.12.007.
[27] J.-J. Wang, Y.-Y. Jing, C.-F. Zhang, J.-H. Zhao, Renew. Sustain. Energy Rev. 13 (9) (2009) 2263–2278, https://doi.org/10.1016/j.rser.2009.06.021.
[28] A. Kumar et al., Renew. Sustain. Energy Rev. 69 (2017) 596–609, https://doi.org/10.1016/j.rser.2016.11.191.
[29] Y. Choi, J. Suh, S.-M. Kim, Appl. Sci. 9 (9) (2019) 1960, https://doi.org/10.3390/app9091960.
[30] Thomas L. Saaty, *The analytic process: planning, priority setting, resources allocation*, 1980. [Online]. Available: https://scholar.google.com/citations?user=mcapoueaaaaj&hl=en&oi=sra.
[31] L.A. Zadeh, *Fuzzy sets*, 8th ed., 1965.
[32] P.C. Fishburn, Oper. Res. 15 (3) (1967) 537–542, https://doi.org/10.1287/opre.15.3.537.
[33] N.H. Anderson, Psychon Sci. 8 (6) (1967) 227–228, https://doi.org/10.3758/BF03331634.
[34] J. Jensen, E. Christensen, Sci. Total Environ. 56 (1986) 265–276, https://doi.org/10.1016/0048-9697(86)90331-1.
[35] P.W. Bridgman, Dimensional Analysis (Revised edition), Yale University Press, New Haven, CT, U.S.A, 1922.
[36] R. Benayoun, B. Roy, B. Sussmann, *ELECTRE: Une methode pour quider le choix en presence de points de vue multiples.*: Note Trav. 49, Dir. Sci., Soc. Econ. Math. Appl., Paris, 1966.
[37] C.-L. Hwang, K. Yoon, *Multiple attribute decision making: Methods and applications: a state the Art Survey*. Berlin [etc.], Springer, 1981.
[38] W. Edwards, J.R. Newman, Multiattribute Evaluation, Beverly Hills, Calif., London, Sage, 1982.
[39] J.P. Brans, P. Vincke, Manage. Sci. 31 (6) (1985) 647–656, https://doi.org/10.1287/mnsc.31.6.647.
[40] N. Balakrishnan, T. Colton, B. Everitt, W.W. Piegorsch, F. Ruggeri, J.L. Teugels (Eds.) *Wiley StatsRef: Statistics reference online*. John Wiley & Sons, Inc, Hoboken, NJ, 2014.
[41] T.P. Fluri, Energy Policy 37 (12) (2009) 5075–5080, https://doi.org/10.1016/j.enpol.2009.07.017.
[42] E. Zawilska, M.J. Brooks, Renewable Energy 36 (12) (2011) 3433–3438, https://doi.org/10.1016/j.renene.2011.05.023.
[43] H.E. Colak, T. Memisoglu, Y. Gercek, Renewable Energy 149 (2020) 565–576, https://doi.org/10.1016/j.renene.2019.12.078.
[44] I. Gašparović, M. Gašparović, Remote Sensing 11 (12) (2019) 1481, https://doi.org/10.3390/rs11121481.
[45] R. Djebbar, D. Belanger, D. Boutin, E. Weterings, M. Poirier, Energy Proc. 49 (2013) 2303–2312, https://doi.org/10.1016/j.egypro.2014.03.244.
[46] J.R. Janke, Renewable Energy 35 (10) (2010) 2228–2234, https://doi.org/10.1016/j.renene.2010.03.014.
[47] R. Ramanathan, L.S. Ganesh, Socio-Econ. Plann. Sci. 29 (3) (1995) 197–218, https://doi.org/10.1016/0038-0121(95)00013-C.
[48] M. Ibarra, I. Gherboudj, A. Al Rished, H. Ghedira, in: Abu Dhabi, United Arab Emirates, 2017, p. 160015.
[49] A. Sunarso, K. Ibrahim-Bathis, S.A. Murti, I. Budiarto, H.S. Ruiz, Sustainability 12 (15) (2020) 6283, https://doi.org/10.3390/su12156283.
[50] H.S. Ruiz, A. Sunarso, K. Ibrahim-Bathis, S.A. Murti, I. Budiarto, Energy Rep. 6 (2020) 3249–3263, https://doi.org/10.1016/j.egyr.2020.11.198.
[51] L. Sun et al., Resour. Conserv. Recycl. 168 (2021) 105306, https://doi.org/10.1016/j.resconrec.2020.105306.
[52] A. Alami Merrouni, F. Elwali Elalaoui, A. Ghennioui, A. Mezrhab, A. Mezrhab, Sol. Energy 166 (2018) 2–12, https://doi.org/10.1016/j.solener.2018.03.038.
[53] G. Rediske, J.C.M. Siluk, L. Michels, P.D. Rigo, C.B. Rosa, G. Cugler, Energy 197 (2020) 117167, https://doi.org/10.1016/j.energy.2020.117167.
[54] M. Huda, K. Okajima, K. Suzuki, Energy Proc. 142 (2017) 2554–2560, https://doi.org/10.1016/j.egypro.2017.12.091.
[55] S. Ziuku, L. Seyitini, B. Mapurisa, D. Chikodzi, K. van Kuijk, Energy Sustain. Dev. 23 (2014) 220–227, https://doi.org/10.1016/j.esd.2014.07.006.
[56] U. Tempa, J.G. Singh, in: International Conference on Electrical and Electronics Engineering - ICE3-2020: February 14-15, 2020, Gorakhpur, India, 2020, pp. 705–710.
[57] F. Kemausuor, E. Adkins, I. Adu-Poku, A. Brew-Hammond, V. Modi, Energy Sustain. Dev. 19 (2014) 92–101, https://doi.org/10.1016/j.esd.2013.12.009.
[58] F. Kemausuor, G.Y. Obeng, A. Brew-Hammond, A. Duker, Renew. Sustain. Energy Rev. 15 (9) (2011) 5143–5154, https://doi.org/10.1016/j.rser.2011.07.041.
[59] S. Raikar, S. Adamson, in: Renewable Energy Finance, Elsevier, 2020, pp. 185–220.
[60] C. Tjengdrawira, Richter, Mauricio, et al., Review and Gap Analyses of Technical Assumptions in PV Electricity Cost, Report on Current Practices in How Technical Assumptions Are Accounted in PV Investment Cost Calculation, 2016.
[61] IRENA, Renewable Power Generation Costs 2020, [Online]. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jun/IRENA_Power_Generation_Costs_2020.pdf.
[62] E.B. Agyekum, V.I. Velkin, Sustainable Energy Technol. Assess. 40 (2020) 100763, https://doi.org/10.1016/j.seta.2020.100763.
[63] International Renewable Energy Agency (IRENA), Estimating the Renewable Energy Potential in Africa: A GIS-based approach.
[64] International Renewable Energy Agency (IRENA), Unleashing the solar potential in ECOWAS: Seeking areas of opportunity.
[65] The World Factbook, *Ghana - The World Factbook*. [Online]. Available: https://www.cia.gov/the-world-factbook/countries/ghana/#geography (accessed: Dec. 20 2021).
[66] Worldfacts, *Geography of Ghana - Geographical Regions, Rivers and Lakes, Climate.* [Online]. Available: http://worldfacts.us/Ghana-geography.htm (accessed: Dec. 20 2021).
[67] Ghana Statistical Service, 2021 Population and Housing Census. Provisional Results Press Release, [Online]. Available: https://statsghana.gov.gh/gssmain/storage/img/infobank/2021%20PHC%20Provisional%20Results%20Press%20Release.pdf.
[68] Ghana Permanent Mission to the United Nations, *Map & Regions in Ghana - Ghana Permanent Mission to the United Nations.* [Online]. Available: https://www.ghanamissionun.org/map-regions-in-ghana/ (accessed: Dec. 20 2021).
[69] O. Marinoni, Comput. Geosci. 30 (6) (2004) 637–646, https://doi.org/10.1016/j.cageo.2004.03.010.
[70] Edward D. Wagner, Public key infrastructure (PKI) and virtual private network (VPN) compared using an utility function and the analytic hierarchy process (AHP), 2002. [Online]. Available: https://vtechworks.lib.vt.edu/bitstream/handle/10919/32685/thesiswagner.pdf?sequence=1&isAllowed=y.
[71] T. Huang, S. Wang, Q. Yang, J. Li, *A GIS-based assessment of large-scale PV potential in China*, 2018. Accessed: Jun. 14 2021. [Online]. Available: https://reader.elsevier.com/reader/sd/pii/S1876610218306702?token=39DFDB0904AFDF2A86FD5EB0FF3F98B28FEC330B4B1A221374A739BD4ECAB5469B254C5077B22BC177913B7E8FD5166A.
[72] E. Noorollahi, D. Fadai, M. Akbarpour Shirazi, S. Ghodsipour, Energies 9 (8) (2016) 643, https://doi.org/10.3390/en9080643.
[73] T. Ramachandra, Solar energy potential assessment using GIS, *undefined*, 2007.
[74] G. Ghasemi, Y. Noorollahi, H. Alavi, M. Marzband, M. Shahbazi, Renewable Energy 138 (2019) 1250–1261, https://doi.org/10.1016/j.renene.2019.02.068.
[75] World Bank Group, *Global Solar Atlas*. [Online]. Available: https://globalsolaratlas.info/map?c=7.966758,-1.032715,7&r=GHA (accessed: Jun. 14 2021).
[76] Global Terrain Slope and Aspect Data, *IIASA - Land Use Change and Agriculture Program*. [Online]. Available: http://webarchive.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML/global-terrain-slope-download.html?sb=7 (accessed: Jun. 14 2021).
[77] Worldpop, *WorldPop:: Population Counts*. [Online]. Available: https://www.worldpop.org/geodata/summary?id=139 (accessed: Dec. 9 2021).
[78] World Bank, *Ghana Electricity Transmission Network: Africa Infrastructure Country Diagnostics (AICD).* [Online]. Available: https://datacatalog.worldbank.org/dataset/ghana-electricity-transmission-network (accessed: Jun. 14 2021).
[79] C. Hernández, R. Barraza, A. Saez, M. Ibarra, D. Estay, Energies 13 (9) (2020) 2131, https://doi.org/10.3390/en13092131.
[80] M. Balghouthi, S.E. Trabelsi, M.B. Amara, A.B.H. Ali, A. Guizani, Renew. Sustain. Energy Rev. 56 (2016) 1227–1248, https://doi.org/10.1016/j.rser.2015.12.052.
[81] L. Dawson, P. Schlyter, Energy Policy 47 (2012) 91–101, https://doi.org/10.1016/j.enpol.2012.04.025.
[82] C. Sharma, A.K. Sharma, S.C. Mullick, T.C. Kandpal, Renew. Sustain. Energy Rev. 42 (2015) 902–912, https://doi.org/10.1016/j.rser.2014.10.059.
[83] World Bank, *Ghana Rivers*. [Online]. Available: https://datacatalog.worldbank.org/dataset/ghana-rivers (accessed: Jun. 14 2021).
[84] M. Uyan, Renew. Sustain. Energy Rev. 28 (2013) 11–17, https://doi.org/10.1016/j.rser.2013.07.042.
[85] UNEP-WCMC and IUCN, *Protected Planet: The World Database: Protected Areas (WDPA)*. Cambridge, UK, 2021. [Online]. Available: www.protectedplanet.net.
[86] M. Šúri, T.A. Huld, E.D. Dunlop, H.A. Ossenbrink, Sol. Energy 81 (10) (2007) 1295–1305, https://doi.org/10.1016/j.solener.2006.12.007.
[87] Y. Sun, A. Hof, R. Wang, J. Liu, Y. Lin, D. Yang, Energy Policy 58 (2013) 248–259, https://doi.org/10.1016/j.enpol.2013.03.002.
[88] X. Ouyang, B. Lin, Energy Policy 70 (2014) 64–73, https://doi.org/10.1016/j.enpol.2014.03.030.
[89] W. Short, D.J. Packey, T. Holt, A manual for the economic evaluation of energy efficiency and renewable energy technologies, 1995.
[90] International Renewable Energy Agency (IRENA), IRENA Cost and Competitive Indicators: Rooftop solar PV.
[91] Ghana Open Data Initiative, *Shapefiles of all Regions in Ghana 2010 (10 regions) | Ghana Open Data Initiative*. [Online]. Available: https://data.gov.gh/dataset/shapefiles-all-regions-ghana-2010-10-regions (accessed: Jun. 14 2021).
[92] International Renewable Energy Agency (IRENA), Solar PV in Africa: Costs and Markets.

Paper 3:

Green hydrogen potential assessment in Ghana: application of PEM electrolysis process and geospatial-multi-criteria approach[6]

[6] referenced as: M. Asare-Addo, "Green hydrogen potential assessment in Ghana: application of PEM electrolysis process and geospatial-multi-criteria approach," *International Journal of Sustainable Energy*, vol. 42, no. 1, pp. 1202–1225, 2023, doi: 10.1080/14786451.2023.2256892.

INTERNATIONAL JOURNAL OF SUSTAINABLE ENERGY
2023, VOL. 42, NO. 1, 1202–1225
https://doi.org/10.1080/14786451.2023.2256892

Green hydrogen potential assessment in Ghana: application of PEM electrolysis process and geospatial-multi-criteria approach

Mary Asare-Addo

Department of Energy and Environmental Management, Europa-Universität Flensburg, Flensburg, Germany

ABSTRACT

With green hydrogen gaining traction as a viable sustainable energy option, the present study explores the potential of producing green hydrogen from wind and solar energy in Ghana. The study combined the use of geospatial multi-criteria approach and PEM electrolysis process to estimate the geographical and technical potential of the selected two renewable resources. The study also included an assessment of potential areas for grid integration. Technology specifications of a monocrystalline solar PV module and 1 MW wind turbine module were applied. Results of the assessment show that about 85% of the total land area in the country is available for green hydrogen projects. Technically, capacities of ∼14,196.21 Mt of green hydrogen using solar and ∼10,123.36 Mt/year from wind energy can be produced annually in the country. It was also observed that some regions, especially regions in the northern part of the country even though showed the most favourable locations for solar-based green hydrogen projects with technical potential of over 1500 Mt/year, these regions may not qualify for a grid connected system based on the current electrification policy of the country due to the regions' low population density and distance from the power grid network threshold.

ARTICLE HISTORY
Received 12 June 2023
Accepted 4 September 2023

KEYWORDS
Green hydrogen; decarbonisation; sustainable energy access; water electrolysis; geographic information systems (GIS); multi-criteria approach

1. Introduction

The achievement of net-zero carbon economies and access to sustainable energy will require the development and evolution of new and improved technologies to harness energy from renewable sources. With the increasing call on global leaders and governments to decarbonise their energy systems due to the adverse impact of global warming on the environment and on society, many leaders with the help of researchers are encouraged to explore various sustainable energy or fuel options to diversify their energy systems. For this reason, and aside other renewable energy resources like wind, solar, hydro, biomass, and geothermal, green hydrogen is also gaining increasing traction as a possible alternative source.

Green hydrogen could provide a great opportunity to countries in Sub-Saharan Africa towards achieving sustainable universal energy access and the eradication of energy poverty. Countries in this region could leverage on the rich renewable energy potentials to produce green hydrogen as an alternative source for electricity generation (Herdem et al. 2023), alternative cooking fuel, and for export. Globally about 2.4 billion people still rely on traditional fuels (World Bank 2023b) like charcoal, fuelwood, crop waste and kerosene for cooking with the associated toxic heath

CONTACT Mary Asare-Addo mary.asare-addo@promovierende.uni-flensburg.de
This article has been corrected with minor changes. These changes do not impact the academic content of the article.

implications as well as negative impact on the environment. It is projected to contribute about 6%–18% of total global energy consumption by 2050 (Ball and Weeda 2015; Okunlola, Davis, and Kumar 2022). Hydrogen is also the most abundant element in the universe yet difficult to obtain in its pure form (Acakpovi et al. 2021; Mackenzie 2019). It is a valuable fuel source widely used in the heavy industry like the manufacturing and transport industries. Global demand for hydrogen is about 70 Mt[1]/year (Mackenzie 2019). The greater concern, however, is that, 99% of today's hydrogen is not green but rather generated from hydrocarbons like coal and natural gas contributing substantially to the share of CO_2 emissions released into the atmosphere (Mackenzie 2019). Green hydrogen on the other hand, is not produced with hydrocarbons but from renewable energy resources like solar and wind through electrolysis by splitting water molecules into hydrogen and oxygen. Many developed countries with good penetration of renewable energy (RE) sources are therefore exploring the potential for long-term commercial production of green hydrogen for domestic uses (Okunlola, Davis, and Kumar 2022). About 252 MW cumulative installed capacity of green hydrogen projects were deployed by the end of 2019 and additional 3205 MW of electrolyser for green hydrogen production will be deployed globally by the end of 2025 (Mackenzie 2019).

Ghana, like many countries, is currently exploring other sustainable means of energy to diversify the country's energy mix in order to meet its Agenda 2030 commitments and targets (Energy Commission of Ghana 2019; Ghana – Action Plan for Sustainable Energy for All by 2030, 2012, 'SE4ALL-GHANA ACTION PLAN' 2012). Green hydrogen will therefore provide great opportunity to the country due to the availability of renewable resources like solar and wind; and particularly for solar which the country has in abundance. This is also because countries in the Sun-Belt region, i.e. between 40° north and south of the Equator have higher potential for solar energy than other parts of the world.

Thus, the potential of green hydrogen is a promising option for the country to consider. This technology if properly developed and harnessed, could even be produced on a commercial scale for export as well as to meet the electricity needs at a grid connection level which will also help minimise the risks associated with the over-reliance on a specific fuel source. This is again particularly crucial for a developing country like Ghana that relies on imported fossil fuels to power its thermal plants – the most dominant energy source in the country's energy mix (Asare-Addo 2022; Energy Commission of Ghana 2020; 2021).

Besides, according to the IEA report (IEA – International Energy Agency 2021), the co-location of hydrogen production from renewables often helps to avoid or minimise the costs associated with electricity transmission. Also, electrolysers used for producing green hydrogen can operate dynamically, needing only seconds to operate at maximum capacity and thus can easily be integrated with renewable infrastructure that are frequently disrupted for long or short duration, and can be stored for longer periods in large tanks for later use (Mackenzie 2019). Opportunities for green hydrogen production in the country exist, even for export. According to Mackenzie (Mackenzie 2019), even though green hydrogen might not be currently competitive on the market as projected in most scenarios by 2025, national pilot projects and targets will help generate enough volume to achieve substantial CAPEX decline beyond 2025. Ghana however as at the end of 2022 does not have a hydrogen energy policy or any existing hydrogen initiatives (Ballo et al. 2022).

Hydrogen over the past years has been produced mainly from hydrocarbons. There are currently about four types of hydrogen produced differently based on the kind of resource used, the technology used, and the processing or method used to produce the hydrogen. Aside green hydrogen, which is produced using renewable resources via electrolysis, the other types are produced using fossil fuels with hydrogen and carbon dioxide as end products. Fossil-based hydrogen includes the blue hydrogen which uses Steam Methane Reforming (SMR) plant with carbon capture and storage (CCS) or Coal gasification plant with CCS to convert natural gas or coal into hydrogen and CO_2 as well as stores CO_2 for reuse. Grey hydrogen is also produced using SMR or coal gasification plant to generate hydrogen and CO_2 using natural gas and coal. Another type is turquoise hydrogen which uses methane pyrolysis plant with carbon capture and utilisation (CCU) to split methane into hydrogen and solid carbon. The present study explores the potential of producing green hydrogen from solar and wind in Ghana using the water electrolysis process and the application of geographic information systems (GIS) techniques.

Many studies have combined the production of green hydrogen via electrolysis with multi-criteria approaches and GIS methods to assess the potential of green hydrogen in many countries. This is mainly due to the spatial characteristics associated with RE sources used for producing the green hydrogen. The application of GIS has become a widely used approach not only in green hydrogen potential assessment but also predominantly used for assessing the potential of RE projects globally. Moreover, the application of GIS in resource assessment has become increasingly important because of the unequal distribution of RE sources across the globe in terms of generation capacity and predominance. For instance, (Bhandari 2022) combined the application of GIS and regression analysis to forecast the potential of solar-to-hydrogen demand across the electricity and transport sectors till 2040 in Niger. The study highlighted that the use of GIS provided a more accurate analysis as it factored in different land use policies which is required to estimate the true hydrogen potential of a location. The application of GIS in the study was however mainly used to evaluate the theoretical and the technical potentials of green hydrogen from solar potential in Niger. Other studies also used GIS to assess the technical potential of green hydrogen (solar and wind) in Canada (Okunlola, Davis, and Kumar 2022). Their study however only focused on the technical potential without estimating the geographical potential. A geospatial approach was also applied to assess the feasibility of green hydrogen from solar, wind and hydropower to replace grey hydrogen production in the EU27 and UK at the regional level (Kakoulaki et al. 2021). Their study focused mainly on the technical potential while briefly highlighting the environmental constraints and techno-economic factors that could affect the generation capacities. Their study however did not explicitly estimate the geographical potential or how land use conditions impacted results of their assessment. (Touili et al. 2018) also performed a techno-economic feasibility study to analyse the potential of generating hydrogen from solar energy in Morocco. The authors used the method of interpolation in the GIS environment to visualised results of their simulation. Their research was also purely technical potential assessment without site suitability evaluation. Another techno-economic potential assessment of green hydrogen production from wind and solar was carried out in Oman by (Okonkwo et al. 2022). A study was also conducted in Turkey to assess and compare offshore and onshore green hydrogen potential from solar (Karayel, Javani, and Dincer 2022). Other country case studies include Algeria (Messaoudi et al. 2019; Rahmouni et al. 2017), South Africa (Ayodele and Munda 2019), Italy (Dagdougui, Ouammi, and Sacile 2011), Iran (Nematollahi et al. 2019), Morocco (Touili et al. 2018), Thailand (Ali et al. 2022), Chile (Gallardo et al. 2021), Jordan (Alrabie and Saidan 2018), Venezuela (Posso and Zambrano 2014), Ecuador (Posso et al. 2016), Brazil (Esteves et al. 2015), and in Turkey (Karayel, Javani, and Dincer 2023). Other studies also include an assessment of the cost of wind-electrolyser fuel cell for energy demand (Genç, Çelik, and Genç 2012), and a technical and financial evaluation of green hydrogen production using solar, wind and hybrid technologies in Egypt (Al-Orabi, Osman, and Sedhom 2023).

For the present case study, a review of the literature shows limited study on green hydrogen potential assessments in Ghana not to mention with a geospatial approach. The present study thus, presents a maiden effort towards quantifying the potential for producing green hydrogen from both wind and solar resources. Few existing studies include a techno-economic assessment of producing hydrogen from wind in Anloga district in the Volta region of Ghana by (Acakpovi et al. 2021). Their assessment however differs entirely from the present study as the present study focuses on the use of solar and wind energy as well as the application of GIS and remote sensing for all the regions. (Topriska et al. 2016) also analysed the feasibility of green hydrogen using solar for cooking in Ghana, Jamaica, and Indonesia. The authors estimated the cooking demand profiles to size the green hydrogen-solar plants for their selected communities using the TRNSYS model. The scope and aim of their research also differ from the present study. And even though their study included GIS, it was used to visualise the results of their analysis. The present study thus differs from these studies in the sense that, for the present study all computations were completely performed in the GIS environment using the model builder as well as with different objectives and approaches. Moreover, the present research unlike other studies, provided an evaluation of the national energy or electrification policies and their implications on energy systems diversification as well as their implications towards the country meeting its decarbonisation targets.

The main objective of this study therefore is to explore the potential of producing green hydrogen from solar and wind in Ghana by estimating their generation capacities at the national and regional levels. To achieve this aim, the geographical and the technical potentials for the two green hydrogen sources were estimated by combining GIS techniques and green hydrogen production by the electrolysis process. The study also went a step further to assess the potential of the green hydrogen produced for a utility-scale system as well as an estimation of the associated potential grid customers in each region.

2. Methodology

This section of the paper explains the approaches used to estimate the geographical and technical capacities for the two selected green hydrogen sources. The study adopted a geospatial approach using spatially explicit satellite images as well as local topographic conditions of Ghana to assess the site feasibility for the selected green hydrogen potentials in the country. The geospatial analysis included the use of ArcGIS, ArcGIS Pro and Quantum GIS (QGIS) software packages where applicable. Results of the geospatial assessment have been visualised using high-resolution maps and exported into excel using the *zonal statistics* tool and *table to excel* tool to show numerical values of the analysis at all regional levels in the country as shown in Tables 2 and 3. Also, all the input raster datasets used for this study were resampled to a 1 km × 1 km cell resolution (km^2) using the bilinear interpolation technique in the GIS environment to achieve coherence in the output of results of the analysis or modelling. Figure 1 shows the geospatial processes used to estimate

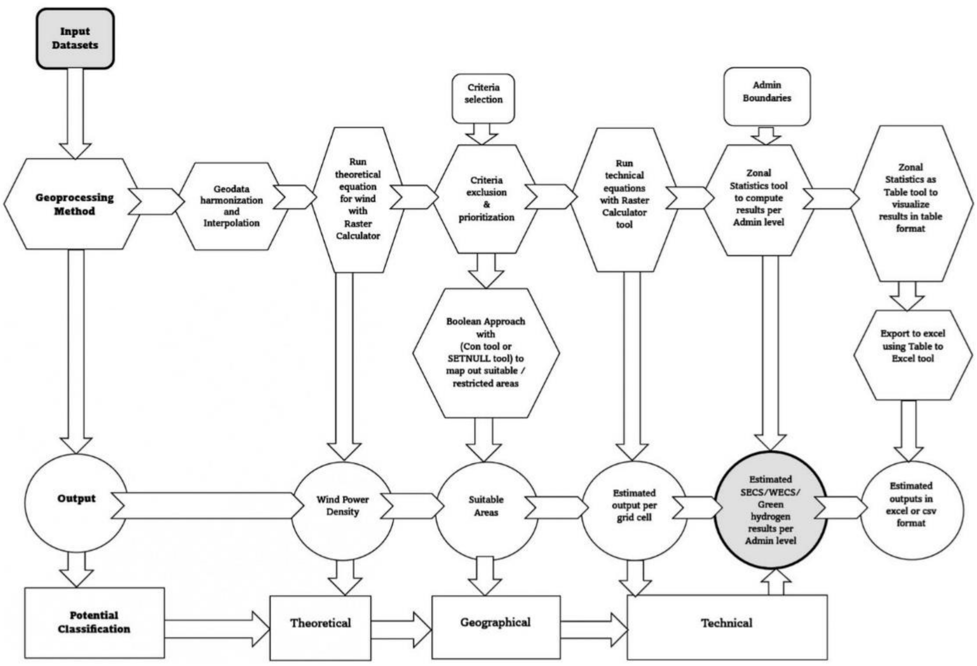


Figure 1. Methodology flowchart.

the resource potentials. Please note that, the theoretical potential was only used to assess the wind power potential of the wind speed. It is also important to clarify that, the economic potential, including the cost of land, were not considered in this study as an assessment of the economic potential is beyond the scope of the current research.

Three scenarios were thus carried out for the green hydrogen using solar and wind technical assessments (i) to compare production with and without power plant spacing constraints, (ii) to evaluate potential for a utility-scale or grid-connected system, (iii) to estimate green hydrogen potential grid-connected customers. The grid connection system analysis was done based on the 20 km proximity to the power grid network requirement rule by the national electrification policy of the country (Asare-Addo 2022; Ghana – Action Plan for Sustainable Energy for All by 2030, 2012, 'SE4ALL-GHANA ACTION PLAN' 2012).

2.1. Brief description of case study country – Ghana

Ghana is located in West Africa and shares its borders with Burkina Faso to the north, Côte d'Ivoire to the west, Togo to the east, and to the south, lies the Gulf of Guinea and the Atlantic Ocean, as shown in Figure 2. The country is a member of the United Nations and like other member countries, has pledged its commitment to decarbonise and provide sustainable energy for all of its citizens. In that regard, the country had set an ambitious target to reach universal energy access by 2020, which was also in line with the country's 2010 National Energy Strategy (NES) (Ghana – Action Plan for Sustainable Energy for All by 2030). This goal however could not be realised even though significant progress has been made since the year of this commitment in 2016 (Energy Commission of Ghana 2020) with an increased electrification rate from 79% to

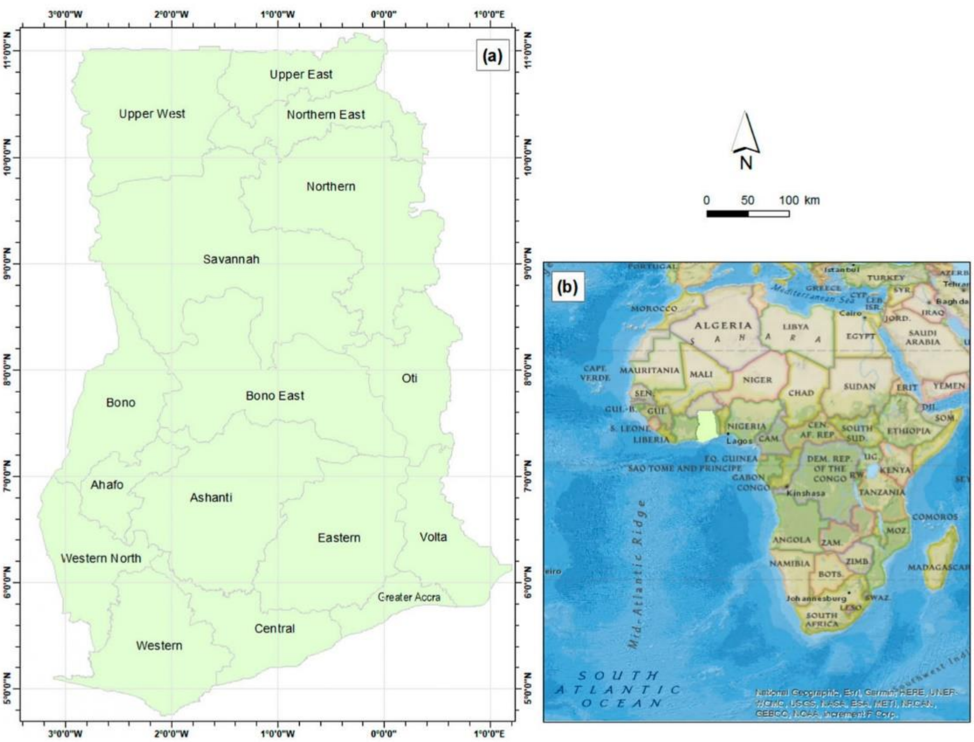


Figure 2. Spatial representation of case study country, (a) Map of Ghana with regional boundaries, (b) Geographical location of Ghana.

~85% in 2020 (World Bank 2023a). Progress towards decarbonisation has nonetheless been slow as thermal power remains the main source of energy in the country's generation mix (Asare-Addo 2022; Energy Commission of Ghana 2020) and accounts for 66.4% (Energy Commission of Ghana 2021) and, 32.9% from hydropower and only about 0.7% from renewables (Energy Commission of Ghana 2021). Moreso, despite an existing renewable energy policy (Energy Commission of Ghana 2019), the country, however, as at the end of 2022 does not have a policy on hydrogen or existing hydrogen project (Ballo et al. 2022). Opportunities to increase the share of renewables exist for the country due to its geographical location that has great potential for solar and even wind which are good sources for large-scale green hydrogen production.

2.2. Geographical potential assessment

This basically refers to the part of the total land area that is available and feasible for the development of renewable energy projects. The geographical potential generally gives insights into the characteristics of the terrain or topography of the land as well as the atmospheric conditions of the location that must be present to ensure optimal energy generation and operation of the power plant. The concept can also be extended to include other quantifiable characteristics of the location such as the social acceptability conditions like level of noise pollution by the power plants, exclusion of environmental protected areas, land use constraints, and conformity to national energy policy or programmes (e.g. marking out areas for utility-scale production or for off-grid electrification).

For the present study, not only were the atmospheric viability of the wind and solar resources considered, but also all protected areas or conservation sites were completely excluded from the analysis to conserve the environment. The geographical potential assessment thus, also marks the first reduction in the generation capacities of the green hydrogen production as part of the total land area of Ghana is excluded from the assessment. Please note that and as already mentioned, the site suitability criteria used though may be generic to certain resource potential assessments like solar and wind, there may exist considerable differences in other studies based on the scope and objective of the study. The land suitability criteria considered in this study include the following: digital elevation model of the terrain, exclusion of protected areas, 20 km proximity to the power grid system, and population or customer density within the regions as shown in Figure 3. The digital elevation model or the elevation data was used to estimate the actual air density of the location as shown in Equation (7). And the grid network and the population density datasets were used to estimate the green hydrogen generation capacities within a 20 km grid proximity buffer for grid connection or utility-scale system (Asare-Addo 2022; Ghana – Action Plan for Sustainable Energy for All by 2030), as well as to estimate the number of potential grid customers within the region.

The Boolean method *(0,1)* in the GIS environment was used to delimit suitable sites and restricted or excluded areas. Thus, all restricted areas were assigned the value *0* and *1* for all suitable areas. Further details of the Boolean concept can be found here (Esri 2016). To assess the geographical potential, the following formula was adopted (Mary 2021):

$$LS_{GH} = \sum_{i=1}^{n} w_i SC_i \prod_{j=0}^{m} R_j \quad (1)$$

where LS_{GH} is the land suitability for siting the green hydrogen plant; w_i is the Boolean weight for the suitability criteria; SC_i is the suitability criteria; and R_j is the area restriction criteria.

2.3. Technical potential assessment

The technical potential basically refers to the amount of green hydrogen that the solar and wind conversion systems can generate over the power plants lifetime given the solar and wind resources

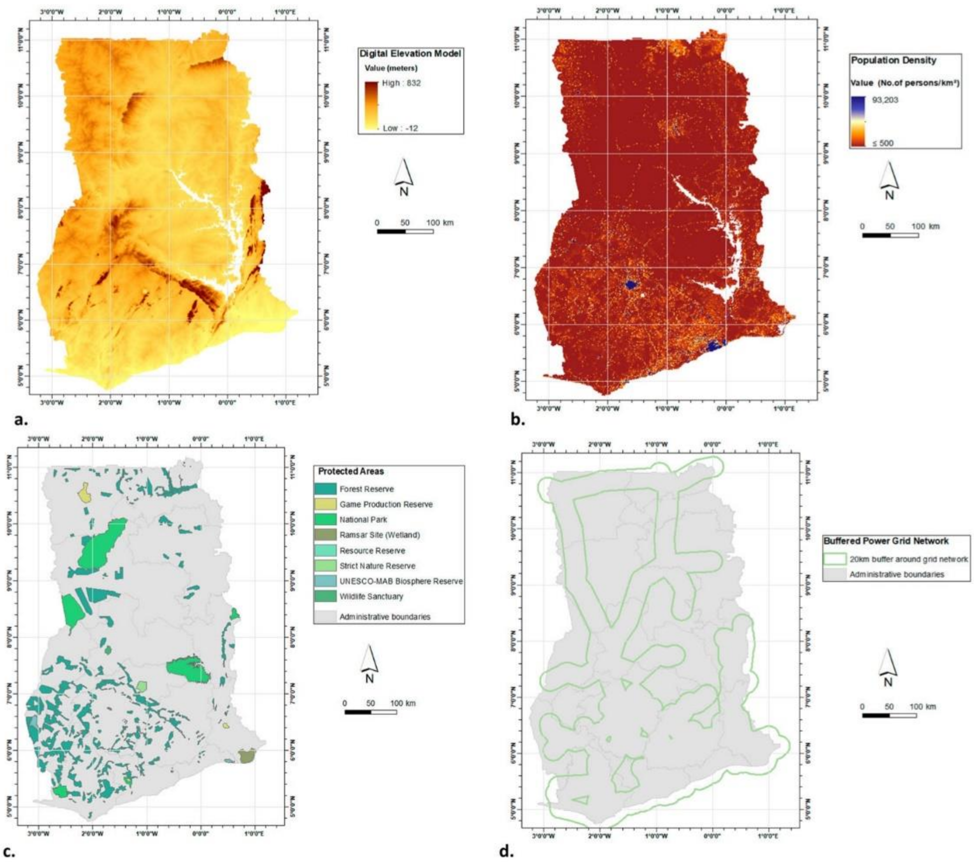


Figure 3. Geospatial data inputs for the land suitability analysis: a. Elevation map; b. Population density map; c. restricted areas; d 20 km buffer distance around grid network.

as shown in Figures 5 and 7. This also includes for this study, the amount of hydrogen mass that the power plants can produce given the geographical potential or the available land area. The production of green hydrogen from the solar PV and the wind turbine required two separate methods. First was to estimate the amount of energy that the solar (SECS) and wind (WECS) conversions systems or power plants can generate. Table 1 shows the input specifications used for the technical potential modelling. The next step was to estimate the amount of hydrogen (M_{H_2}) that the electrolyser conversion system can produce given the energy generated by the solar and wind power plants. In addition, the study also estimated the impact of spacing factor in the overall generation capacities of the green hydrogen power plant, as shown in Tables 2 and 3.

Table 1. Technical specifications for the green hydrogen modelling.

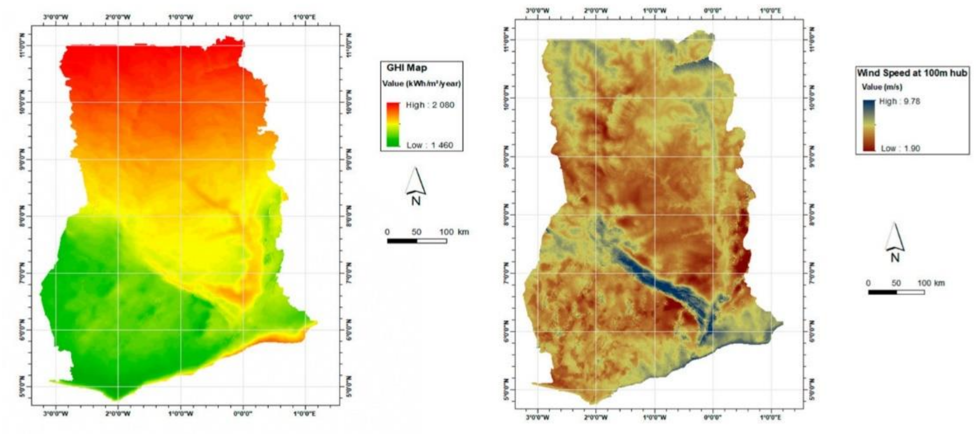
Component	Value
Photovoltaic module efficiency (η_{PV})	17.5%
Spacing factor for Photovoltaic module ($\eta_{\phi_{SECS}}$)	2
Power conditioning efficiency (η_{PC})	85%
Electrolysis system efficiency (η_{Elec})	75%
Rectifier efficiency (η_{Rec})	90%
Hydrogen Higher Heating value (HHV_{H_2})	39.4 kWh/kg
Gearbox efficiency (η_{gb})	85%
Generator efficiency (η_{gen})	95%

Table 2. Summary statistics for the solar-based green hydrogen analysis.

Region Name	Actual land (km^2)	Geographical Potential (%)	$SECS_{MAX}$ withSpacing (GWh/year)	$SECS_{TOTAL}$ withSpacing (TWh/year)	$SECS_{MAX}$ NoSpacing (GWh/year)	$SECS_{TOTAL}$ NoSpacing (TWh/year)	$Hydrogen_{MAX}$ withSpacing (Tonnes/year)	$Hydrogen_{TOTAL}$ withSpacing (Mt/year)	$Hydrogen_{MAX}$ NoSpacing (Tonnes/year)	$Hydrogen_{TOTAL}$ NoSpacing (Mt/ year)	$Hydrogen_{MAX}$ NoSpacing and within 20 km Grid Network (Tonnes/year)	$Hydrogen_{TOTAL}$ NoSpacing and within 20 km Grid Network (Mt/year)	Total Population	Population within 20 km Grid within the region (%)
Ahafo	5195.47	74.48%	133.13	6492.93	266.26	12,985.87	2534.22	123.60	5068.45	247.19	5068.45	48.43	584,877	18.10%
Ashanti	24,370.22	83.78%	140.57	35,435.45	281.14	70,870.91	2675.80	674.53	5351.60	1349.07	5351.60	945.32	5,871,660	94.12%
Bono	11,648.92	80.08%	140.57	16,061.54	281.14	32,123.07	2675.80	305.74	5351.60	611.48	5238.34	279.98	1,128,141	64.36%
Bono East	23,247.90	85.61%	143.54	36,270.72	287.09	72,541.44	2732.43	690.43	5464.86	1380.86	5464.86	754.72	1,157,074	71.67%
Central	9659.34	91.91%	142.80	14,894.95	285.60	29,789.90	2718.27	283.53	5436.55	567.07	5436.55	482.97	2,682,408	92.29%
Eastern	18,958.36	92.21%	144.29	30,654.39	288.58	61,308.79	2746.59	583.52	5493.18	1167.05	5493.18	1028.48	3,285,799	97.53%
Greater Accra	3698.86	96.54%	147.26	6321.59	294.52	12,643.18	2803.22	120.33	5606.44	240.67	5606.44	240.67	4,896,589	100.00%
Northern	24,842.42	95.95%	149.49	45,513.71	298.99	91,027.43	2845.69	866.38	5691.39	1732.76	5663.07	497.75	1,843,100	49.55%
Northern East	9071.41	94.82%	152.47	16,980.45	304.94	33,960.90	2902.32	323.23	5804.65	646.46	5748.02	151.99	558,297	24.78%
Oti	11,066.07	93.68%	142.80	18,682.96	285.60	37,365.93	2718.27	355.64	5436.55	711.28	5379.92	423.55	825,973	63.62%
Savannah	35,853.03	77.47%	149.49	52,370.22	298.99	104,740.45	2845.69	996.90	5691.39	1993.79	5663.07	931.25	661,612	52.26%
Upper East	8618.64	84.51%	153.96	14,675.33	307.91	29,350.66	2930.64	279.35	5861.28	558.71	5861.28	383.33	1,262,883	85.36%
Upper West	19,032.96	92.95%	154.70	35,348.75	309.40	70,697.50	2944.80	672.88	5889.59	1345.76	5889.59	719.93	838,098	71.18%
Volta	9827.90	90.60%	145.77	15,547.96	291.55	31,095.92	2774.90	295.96	5549.81	591.93	5549.81	578.92	1,881,531	97.77%
Western	14,257.30	79.09%	138.34	18,633.07	276.68	37,266.14	2633.33	354.69	5266.66	709.38	5266.66	571.82	1,961,022	90.07%
Western North	10,080.18	53.58%	131.64	9003.11	263.29	18,006.23	2505.91	171.38	5011.82	342.76	5011.82	223.31	878,605	68.20%
Total	**239,428.99**	**85.45%**		**372,887.15**		**745,774.32**		**7098.11**		**14,196.21**		**8262.40**	**30,317,669.77**	**84.33%**

Table 3. Summary statistics for the wind-based green hydrogen analysis.

Region Name	Actual land (km^2)	Geographical Potential (%)	Air $Density_{Max}$ (kg/m^3)	WPD_{Max}(W/m^2/year)	$WECS_{MAX}$ withSpacing (GWh/year)	$WECS_{TOTAL}$ withSpacing (TWh/year)	$WECS_{MAX}$ NoSpacing (GWh/year)	$WECS_{TOTAL}$ NoSpacing (TWh/year)	$Hydrogen_{MAX}$ withSpacing (Tonnes/year)	$Hydrogen_{TOTAL}$ withSpacing (Mt/year)	$Hydrogen_{MAX}$ NoSpacing (Tonnes/year)	$Hydrogen_{TOTAL}$ NoSpacing (Mt/ year)	$Hydrogen_{MAX}$ NoSpacing and within 20 km Grid Network (Tonnes/year)	$Hydrogen_{TOTAL}$ NoSpacing and within 20 km Grid Network (Mt/ year)	Total Population	Population within 20 km Grid within the region (%)
Ahafo	5195.47	74.48%	1.2084	122.85	3.38	68.21	520.57	10,503.97	57.91	1.17	8918.40	179.95	8000.31	39.66	584,877.03	18.10%
Ashanti	24,370.22	83.78%	1.2186	465.96	12.82	375.87	1974.44	57,883.58	219.65	6.44	33,826.13	991.66	33,826.13	745.66	5,871,660.15	94.12%
Bono	11,648.92	80.08%	1.2133	393.54	10.83	206.48	1667.60	31,797.78	185.51	3.54	28,569.30	544.76	12,270.76	285.54	1,128,141.31	64.36%
Bono East	23,247.90	85.61%	1.2162	195.46	5.38	284.46	828.25	43,807.25	92.14	4.87	14,189.53	750.50	14,189.53	508.87	1,157,073.79	71.67%
Central	9659.34	91.91%	1.2248	247.04	6.80	215.09	1046.81	33,123.86	116.45	3.68	17,933.95	567.48	17,933.95	500.53	2,682,408.02	92.29%
Eastern	18,958.36	92.21%	1.2244	555.47	15.28	334.11	2353.74	51,452.74	261.85	5.72	40,324.30	881.49	40,324.30	840.38	3,285,799.40	97.53%
Greater Accra	3,698.86	96.54%	1.2264	351.23	9.66	126.48	1488.30	19,477.19	165.57	2.17	25,497.45	333.68	25,497.45	333.68	4,896,589.01	100.00%
Northern	24,842.42	95.95%	1.2156	140.01	3.85	492.13	593.27	75,788.69	66.00	8.43	10,163.83	1298.41	7750.32	382.96	1,843,099.65	49.55%
Northern East	9071.41	94.82%	1.2117	201.85	5.55	192.51	855.31	29,646.10	95.15	3.30	14,653.14	507.90	11,310.42	110.96	558,297.00	24.78%
Oti	11,066.07	93.68%	1.2166	145.91	4.01	114.65	618.27	17,655.36	68.78	1.96	10,592.19	302.47	10,592.19	154.45	825,972.68	63.62%
Savannah	35,853.03	77.47%	1.2159	103.16	2.84	379.91	437.11	58,506.21	48.63	6.51	7488.58	1002.33	7488.58	519.10	661,612.23	52.26%
Upper East	8618.64	84.51%	1.2096	234.59	6.45	172.50	994.05	26,565.30	110.58	2.96	17,029.97	455.12	17,029.97	336.91	1,262,882.84	85.36%
Upper West	19,032.96	92.95%	1.2076	139.65	3.84	416.04	591.75	64,070.61	65.83	7.13	10,137.79	1097.66	10,137.79	642.89	838,098.12	71.18%
Volta	9827.90	90.60%	1.2252	267.64	7.36	182.32	1134.08	28,077.94	126.16	3.12	19,429.07	481.03	19,429.07	472.70	1,881,530.86	97.77%
Western	14,257.30	79.09%	1.2254	162.34	4.47	192.20	687.91	29,598.79	76.53	3.29	11,785.26	507.09	11,785.26	406.67	1,961,022.38	90.07%
Western North	10,080.18	53.58%	1.2219	166.07	4.57	84.08	703.69	12,948.64	78.28	1.44	12,055.59	221.84	12,055.59	135.91	878,605.31	68.20%
Total	**239,428.99**	**85.45%**				**3837.04**		**590,904.02**		**65.74**		**10,123.36**		**6416.87**	**30,317,669.77**	**84.33%**



a. Global Horizontal Irradiance b. Extrapolated wind speed distribution

Figure 4. Visualisation of the solar irradiance and wind speed distribution.

2.3.1. Solar energy technical potential

2.3.1.1. Solar energy from the conversion system (SECS). Firstly, the solar energy[2] generation capacity for all locations at the regional level were estimated. This was done to quantify the amount of solar energy that the selected solar PV module can generate. The solar radiation of the location as well as specifications of the solar PV module were used to compute the total solar energy potential of a location (see Table 1). The annual average solar irradiance in Ghana and as visualised in Figure 4 ranges from 1 460 kWh/m²/year to 2 080 kWh/m²/year from the bilinear resampling technique used. The data was downloaded from the global solar atlas platform (Global Solar Atlas 2023). A monocrystalline PV module was used because of its maturity on the solar market as well as its high efficiency compared to the other solar modules (Gaur and Tiwari 2013; IEA 2023). Several methods have been used in the literature to estimate the technical energy potential of a PV module, examples include (Asare-Addo 2022; Bhandari 2022; Dagdougui, Ouammi, and Sacile 2011; Gerbo, Suryabhagavan, and Raghuvanshi 2022; Koko 2022; Leiblein et al. 2021; Okunlola, Davis, and Kumar 2022; Rahmouni et al. 2016; Sunarso et al. 2020; Touili et al. 2018). The methods applied are generally dependent on the aim and scope of the research, other studies have included other PV specifications and requirements in the PV technical potential assessment such the derating factor, and the capacity factor which could significantly affect results of the analysis. For this study, a spacing factor for the solar PV was introduced into the model to account for instances where spacing is required. The spacing assumptions used for the solar PV system generally ranges from 1.4 to 5 as applied in the African region (Asare-Addo 2022; International Renewable Energy Agency 2014; Yushchenko et al. 2018). For this study, the below formula was used to estimate the total solar energy capacities by the selected PV module (Berrada and Laasmi 2021; Touili et al. 2018):

$$TP_{SECS} = GHI * \eta_{PV} * \eta_{PC} \quad (2)$$

With spacing factor:

$$TP_{SECS} = GHI * \eta_{PV} * \eta_{PC} * \eta_{\phi_{SECS}} \quad (3)$$

where TP_{SECS} is the total solar energy technical potential from the PV module in GWh/km²/year. GHI is the annual solar irradiance in kWh/m²/year; η_{PV} is the PV efficiency (%), and η_{PC} is the power conditioning efficiency used to shape and condition the solar energy produced by the PV plant (%), and $\eta_{\phi_{SECS}}$ is the spacing factor, here a spacing factor of 2 was applied.

2.3.1.2. Solar energy to hydrogen: the water electrolysis modelling. The electricity generated by the PV plant then undergoes the water electrolysis process. There are different types of water electrolysis technologies, which are the alkaline and the Proton Exchange Membrane (PEM) electrolysers. For this study the PEM electrolyser system was used due to its high life cycle, efficiency and compatibility with the variability of electricity generated from renewable sources (Alshehri et al. 2019; Ayodele and Munda 2019; Nematollahi et al. 2019; Okunlola, Davis, and Kumar 2022). Moreso, due to the hydrogen pressure of 1.2 bar, hydrogen produced from PEM electrolyser do not require compression and can be stored directly or linked to a pipeline (Dagdougui, Ouammi, and Sacile 2011; Touili et al. 2018). The PEM electrolyser used is assumed to consume about 54 kWh (power capacity) of energy to produce 1 kg of hydrogen, with higher heating value (HHV) of 39.4 kWh/kg and with 75% efficiency and has the capacity to produce on the average, about 1 Ton per day (~1000 kg/day). The assumptions, specifications and parameters used in the electrolysis process are based on the most widely used values for estimating the potential of green hydrogen from solar (Ali et al. 2022; Dagdougui, Ouammi, and Sacile 2011; Rahmouni et al. 2017; Touili et al. 2018; Yodwong et al. 2020) as shown in Table 1. The mass of green hydrogen using solar was estimated using the equation below (Ali et al. 2022; Boudries 2016; Gouareh et al. 2015; Messaoudi et al. 2019; Rahmouni et al. 2017; Touili et al. 2018):

$$M_{H_2}\ of\ TP_{SECS} = \frac{E_{H_2}}{HHV_{H_2}} = \frac{TP_{SECS} * \eta_{Elec}}{HHV_{H_2}} \tag{4}$$

M_{H_2} is the mass of hydrogen produced from the solar energy conversion system (TP_{SECS}) in tonnes/km²/year, E_{H_2} is the hydrogen electricity produced and required for the power plant in kWh/km²/year. η_{Elec} is the efficiency of the electrolysis system, and HHV_{H_2} is the hydrogen higher heating value in kWh/kg.

2.3.2. Wind energy technical potential

2.3.2.1. Interpolation of the wind speed distribution data. The wind speed distribution data used for this study was downloaded from the global wind atlas portal (Global Wind Atlas 2023) and was readjusted to a 1 km × 1 km resolution to ensure uniformity in the output of the assessment, i.e. to make sure the analysis is carried out at the same grid or cell size. Few interpolation techniques exist, but for this study the bilinear resampling method was used because of its suitability for continuous data like wind speed and the solar radiation data that has been measured and validated over a period of time. At a hub height of 100 m, wind speed distribution in the country ranges from ~1.92 to ~9.84 m/s.

2.3.2.2. Extrapolation of the wind speed hub height. Wind speed regime is recorded at various hub heights to provide insight into the choice of wind turbine to mount on site, either for a small-scale or commercial projects. Lower hub heights are generally ideal for small-scale projects due to the nominal wind speed values or potential. Wind speed at anemometer height of 100 m was used for this study. However, due to wind shear anomalies caused by atmospheric externalities such as variations in altitude, speed frequencies and the frictional effect of the earth surface, it is important to calibrate the wind speed to the hub of the chosen wind turbine for the specific locations to mount the wind turbine. Thus, to estimate the wind shear exponent (α), the earth surface is assumed to be homogenous and was estimated using the power law model (Manwell, McGowan, and Rogers 2009):

$$U_2 = U_1 \left(\frac{Z_2}{Z_1}\right)^{\alpha} \tag{5}$$

U_1 is the wind velocity at the anemometer height Z_1 (at the lower height), U_2 is wind velocity at the turbine height Z_2 (at the upper height), and α is the wind shear exponent which varies with altitude, time, and location. The wind shear value is determined by the terrain type or surface roughness and generally ranges between 0.1 and 0.4 (Liu et al. 2023). For this study, a surface roughness value of 0.03 was assumed given that the wind turbines will be mounted at open agricultural area with very scattered buildings. The extrapolated wind speed distribution thus ranges from 1.90 to 9.78 m/s as shown in Figure 4.

2.3.2.3. Theoretical power of the wind speed. The amount of wind energy generated by the wind turbine depends on the wind power potential of the location. It is therefore important to estimate the theoretical wind power potential of the site. Computing the wind power at the grid cell level is conceptually challenging (Hoogwijk, de Vries, and Turkenburg 2004; Mary 2021) hence the kinetic energy derived from the wind which contains speed and air mass were used to estimate the wind power potential which is referred to as the wind power density (WPD). This was determined using the following equation:

$$WPD = \frac{1}{2}\rho \sum\nolimits_{i=1}^{n} U^3 \ = \ 1/2\rho U^3 \tag{6}$$

WPD is the potential wind power capacity of the wind (W/m^2), ρ is the air density (kg/m^3), and U is the wind speed value (m/s) recorded in n period of time. It is however important to mention that, for this study, unlike as used in many other studies, the air density is not equal to 1.225 kg/m^3 as generally assumed for all locations but rather the actual air density value was estimated for each location considering temperature variations (Asare-Addo 2022) (see Table 3). Hence the ideal gas law which provides a more accurate estimation of the air density of a location above sea level was used. The ideal gas law is given as:

$$\rho = 1.225 - (1.194{*}10^{-4}){*}z \tag{7}$$

z is the elevation of the location above sea level (m).

2.3.2.4. Machine power estimation: yield from the wind turbine. For the wind energy potential assessment, it is also crucial to assess the viability of the site to generate a substantial amount of energy which is generally based on the wind regime and the wind turbine used. Hence, it is imperative to evaluate the wind regime of a location to be able to select the best turbine for optimal capacity generation of the green hydrogen from wind. Based on the onshore wind speed regime of Ghana as visualised in Figure 2, a wind turbine within IEC class III or IV will be appropriate. Hence the NREL 1000 kW (1MW) distributed wind turbine was used for this simulation (Bhaskar and Stehly 2021). The turbine has a conducive cut-in[3] wind speed of 3 m/s, and a cut-out[4] wind speed of 25 m/s, with a rotor diameter of 77 m and 80 m hub height (Bhaskar and Stehly 2021; Lantz et al. 2016). This turbine was selected not only because of the wind speed requirements but also due to its power curve that could be utilised not only for residential purposes but also a potential model for commercial wind farm projects. The first step therefore was to estimate the energy yield by the turbine given the suitable land areas. It is important to mention that computation of the energy potential of local winds is complex due to the wide variations in the wind speed characteristics of the different locations (Mary 2021) – thus, the machine energy outputs are approximated values. As discussed earlier, the wind characteristics of any given wind regime can be well-defined based on the wind distribution. To determine this, there are currently two widely used probability methods used to estimate the wind speed distribution of a location to help in the selection of a well-fit turbine to install on the site; the Rayleigh and the Weibull distribution functions. These methods are used to determine the power densities of locations which in turn are used to estimate the energy output generated by the wind turbine. These two methods differ in the sense that, the Rayleigh distribution function applies only the mean windspeed values whereas the Weibull uses both the mean windspeed and standard deviation values of the wind regime. For this study and a review of the literature show that, the Weibull function provides the best-fit for the wind speed distribution in Ghana (Mary 2021). The Weibull function is given as:

$$P(U) = k/c*\left(\frac{U}{c}\right)^{k-1} \exp\left[-\left(\frac{U}{c}\right)^{k}\right] \tag{8}$$

$$F(U) = 1 - \exp\left[-\left(\frac{U}{c}\right)^{k}\right] \tag{9}$$

$$\bar{U} = c\Gamma(1 + 1/k) \tag{10}$$

$$k = (\sigma U/\bar{U})^{-1.086} \tag{11}$$

k is the shape factor and falls within the range of $1 \leq k < 10$, c is the scale factor and can be solved by substituting Equation (11) into Equation (12) and which also requires the gamma function, Γ. k and c are both functions of the mean wind speed $\bar{U}$; and the standard deviation, σU. U is the wind-speed value.

$$c = \frac{\bar{U}}{\Gamma(1 + 1/k)} \tag{12}$$

The next step then was to determine the wind energy output per location by the chosen wind turbine. This was estimated using the power curve of the turbine. For a given wind regime, expressed as the probability density function $p(U)$, $\bar{P}_w$ which is the actual mean available energy output generated by the wind turbine can be estimated given the following equation (Manwell, McGowan, and Rogers 2009):

$$\bar{P}_w = \int_0^\infty P_w(U)p(U)dU \tag{13}$$

$$\bar{P}_w = \left(\int_0^\infty P_w(U)p(U)dU\right)(t) \tag{14}$$

2.3.2.5. Estimation of the capacity factor (Cf). The capacity factor (***Cf***) of a wind turbine plays a crucial role in selecting the appropriate wind turbine for a given location. It also provides insight into the economic viability of the wind project sites (Ayodele and Munda 2019). The Cf can be expressed as ratio of the actual average power output of the turbine ($\bar{P}_w$) to the rated power output of the turbine (P_r) over a time period (t); where time period is the number of hours in a full year (i.e. 8760 hours/year). The wind turbine capacity factor can thus be estimated by (Manwell, McGowan, and Rogers 2009):

$$Cf = \bar{P}_w / P_r \tag{15}$$

Thus, for a conventional wind turbine, under a steady incoming wind, the mechanical average wind energy that can be extracted from the turbine rotor can be estimated by (Manwell, McGowan, and Rogers 2009; Simpson and Loth 2022):

$$P_w(U) = 1/2\rho A C_p U^3 \tag{16}$$

$P_w(U)$ is the power extracted by the turbine rotor, A is the rotor swept area (m^2) which is $\approx \pi D^2/4$ (D is the rotor diameter (m), and $\pi = 3.1416$), C_p is the maximum power coefficient of the turbine; with a dimensionless theoretical value of 0.59 known as the Betz limit (Manwell, McGowan, and Rogers 2009).

2.3.2.6. Wind energy from the conversion system (WECS). The wind energy conversion system usually consists of the wind turbine, the gearbox, the electrical generator, the power electronic convertor, and the water electrolysis system (Ayodele and Munda 2019; Dagdougui, Ouammi, and Sacile 2011; Okunlola, Davis, and Kumar 2022; Olateju, Kumar, and Secanell 2016). For the wind energy to hydrogen production, the PEM electrolysis system was used and requires a DC electrical energy capacity of 54 kWh to produce 1 kg of hydrogen. The gearbox is usually used to increase the rotational speed of low-speed turbine rotor to a higher speed electrical generator (Ayodele and Munda 2019; Ayodele and Ogunjuyigbe 2015; Okunlola, Davis, and Kumar 2022). The use of the gearbox is also particularly important due to variations in the wind speed distribution across the project sites and considering the use of the same turbine model. In addition, a turbine spacing factor was introduced in this model to minimise the effect of turbulence and to ensure that all the turbines mounted will receive an appreciable amount of the wind speed on a km^2 of land by increasing the rotor swept area radius. By rule of thumb, turbine spacing is generally 3–5 rotors diameter apart and 5–9 rotor diameter between the rows (Gupta 2016). A 3× rotor diameter spacing within the turbines was considered for this study. The electrical energy potential of a typical wind energy conversion system can therefore be estimated using the following model (Ayodele and Munda 2019):

$$TP_{WECS} = P_w(U)*\eta_{gb}*\eta_{gen} \tag{17}$$

With spacing factor:

$$TP_{WECS} = P_w(U)*\eta_{gb}*\eta_{gen} * \eta_{\phi_{WECS}} \tag{18}$$

$$\eta_{\phi_{WECS}} = \frac{\text{available land area}}{\text{spacing value}*\text{rotor diameter}} \tag{19}$$

TP_{WECS} is the total wind energy technical potential extracted from the wind conversion system (GWh/km^2/year), η_{gb} is the gearbox transmission efficiency, η_{gen} is the generator efficiency, and $\eta_{\phi_{WECS}}$ is the increased rotor diameter factor. Please note that $P_w(U)$ already includes rotor diameter exponent one. Thus, the turbine swept area is extended by two rotor diameter.

2.3.2.7. Wind energy to hydrogen: the water electrolysis modelling. To extract and determine the amount of hydrogen that the turbine can generate, the wind energy conversion system was made to go under a water electrolysis using the PEM electrolyser. The electrolysis system for the green hydrogen using wind consists of the extracted wind energy (i.e. wind turbine, the gearbox, and the electrical generator) as well as a AC–DC rectifier to convert the AC voltage of the energy produced by the turbine to a DC voltage output suitable for the electrolyser to operate and also conducive for storage of the hydrogen in high-pressure tanks (Almutairi et al. 2022; Ayodele and Munda 2019). The potential amount of hydrogen that can be produced from the system was modelled using the following equation:

$$M_{H_2} \text{ of } TP_{WECS} = \frac{E_{H_2}}{HHV_{H_2}} = \frac{TP_{WECS}*\ \eta_{Elec}*\ \eta_{Rec}}{HHV_{H_2}} \tag{20}$$

3. Results

This section presents the results of the study. It includes the results of the geographical potential and the technical potential assessment for the two selected green hydrogen systems. Please note that the results of the technical hydrogen potentials are based on the SECS and WECS estimates. Results of the analysis are presented and visualised based on a 1 km^2 grid resolution at the national and regional levels in Ghana. Finally, the study also tried to provide an assessment highlighting the potential of green hydrogen for a grid-connected or utility-scale system given the grid connection policy in the country (Asare-Addo 2022; Ghana – Action Plan for Sustainable Energy for All by 2030, 2012, 'SE4ALL-GHANA ACTION PLAN' 2012), and potential grid-connection customers.

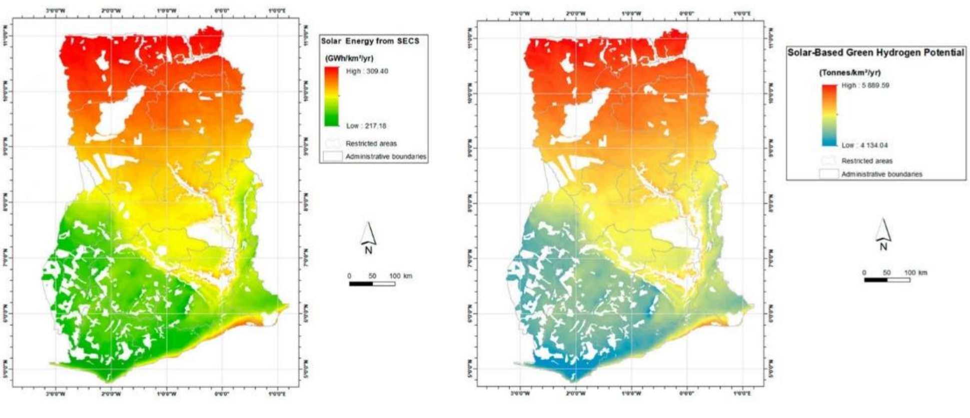
3.1. Geographical potential

Results based on the evaluation of sites for mounting the two green hydrogen power plants have been discussed here. The main purpose of this assessment was to identify suitable sites that will maximise the green hydrogen production while protecting conservation sites. Therefore, all areas that were not socially and environmentally conducive to site the power plants were completely excluded from the analysis. The exclusion criterion was based mainly on the areas occupied by protected zones and that accounted for about 14.55% of total land area, as shown in the summary statistics (Tables 2 and 3). This also shows that based on the recent administrative boundary data used for this study (OCHA & Humanitarian Data Exchange 2021), out of the ~239,429 km² of Ghana's total land area, ~85% is suitable for the production of green hydrogen using solar and wind. The Greater Accra region which is the capital of Ghana even though has the smallest total land area (~3698.86 km²) has the largest geographical potential of 96.45% for the green hydrogen production. Followed by the Northern region with a geographical potential of 95.95% for both the production of green hydrogen from solar and wind. The Greater Accra region is also the most densely populated region. Figures 5 and 7 show maps of study results with the restricted areas.

3.2. Technical potential: results from the conversion systems

3.2.1. Solar-based green hydrogen potential

In this section, the results of the solar energy generated by the solar PV conversion system (SECS) as well as for the electrolysis process are discussed. Green hydrogen using solar basically refers to the production of green hydrogen using the energy generated by the SECS through water electrolysis process with an electrolyser technology. Figure 5 shows maps of the solar energy potential from the SECS as well as with the corresponding green hydrogen from solar generation capacities with no spacing factor considerations. Table 2 also provides summary statistics for the green hydrogen using solar assessment including generation capacities across the regions for the solar PV plant with and without spacing factor considerations. As visualised in Figure 5 and shown in Table 2, each region shows varying generation capacities for both the SECS and for the green hydrogen using solar, which also depicts a direct correlation between the solar intensity or irradiance of the location. The Upper West region recorded the highest solar radiation intensity of 2 080 kWh/m²/year with corresponding SECS and green hydrogen using solar generation capacities of ~309.40 GWh and ~5889.59 Tonnes/year without spacing per km², respectively. However, the region with the largest green hydrogen using solar potential is the Savannah region, with a total



a. Solar energy potential with no spacing.

b. Green hydrogen using solar potential with no spacing.

Figure 5. Solar energy potential from the SECS with corresponding green hydrogen production using solar with no spacing factor.

generation capacity of 1993.79 Mt per year, and about 996.90 Mt/year with spacing considerations. The lowest generation capacity was recorded in the Ahafo region, with a total of 247.19 Mt/year without spacing, and ~123.60 Mt/year with the PV plant spacing, and a maximum SECS energy output of ~266.26 GWh. Nationally, and with respect to the geographical potential, a total of ~14,196.21 Mt of green hydrogen using solar can be produced annually in the country without spacing and ~7098.11 Mt/year when spacing factor is considered. Please note that the Ahafo region is however not the smallest region per total land area (see Table 2).

Figure 6 also shows the geospatial model used to compute the solar-based green hydrogen technical potential. The model consists of four geo-processes. As mentioned earlier, the production of green hydrogen using solar involves two separate processes, the first process was to estimate the amount of solar energy that can be generated from the solar PV conversion system (TP_SECS) using the raster calculator in ArcGIS for the calculations, and the next process was to run the extracted solar energy through the electrolyser system to produce the green hydrogen (Mass_Hydrogen). Also as shown in (Equation 3), a spacing factor was also included to estimate how much potential can be generated when spacing of the solar PV module is considered. The spacing was only considered during the TP_SECS estimation which in effect also affected the amount of green hydrogen that can be produced by the electrolyser system.

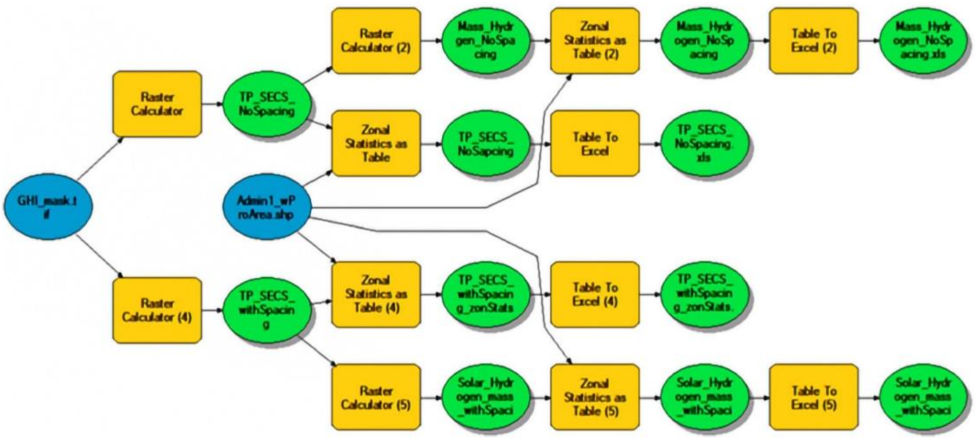
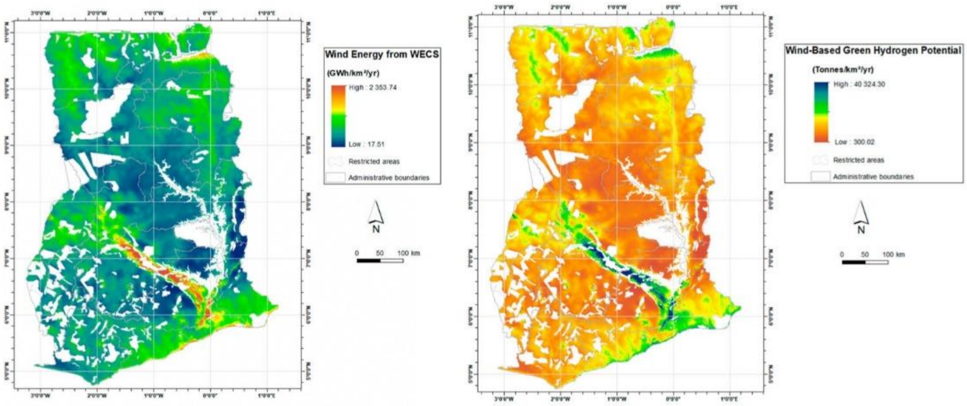


Figure 6. Solar-based green hydrogen technical potential model.

3.2.2. Wind-based green hydrogen potential

This section also presents and explains the results of the wind energy generated by the wind turbine conversion system (WECS) as well as for the electrolysis process. Green hydrogen using wind refers to the process of using the wind energy supplied by the WECS to produce hydrogen mass using an electrolyser technology and through the process known as electrolysis – process of using the renewable energy or electricity to split water into hydrogen and oxygen, while emitting zero-carbon dioxide in the process. Here also, results of the assessment show varying technical potentials across the regions, which also show a direct correlation with the wind speed class. The results have been presented in Figure 7 and in the summary statistics Table 3, including the WPD and the air density estimations used in computing the mechanical energy output generated by the wind turbine. At the national level, a total of ~10,123.36 Mt of green hydrogen using wind can be produced annually with no spacing consideration and about 65.74 Mt/year with consideration to the impact of spacing the wind turbines per suitable or available land area. At the regional level, and with regards to only the technical potential, the Eastern region recorded and showed the most favourable location, with a generation capacity of about 2353.74 GWh from the WECS and 40,324.30 Tonnes/km^2/year and a total capacity of ~881.49 Mt/year of green hydrogen using wind – all without spacing factor, given the maximum extrapolated wind



a. Wind energy potential with no spacing.

b. Green hydrogen using wind potential with no spacing.

Figure 7. Wind energy potential from the WECS with corresponding hydrogen production with no spacing factor.

speed value of 9.78 m/s. Additionally, given spacing considerations, the region could generate a total of ~5.72 Mt/year given the geographical potential. The Savannah region on the other hand recorded the lowest wind energy and green hydrogen given the wind energy generation capacities with no spacing. With a maximum wind speed of 5.89 m/s, the region generated about 437.11 GWh from the WECS. With spacing constraints, the Northern region recorded the largest potential of about 1298.41 Mt/year. Correspondingly, and as mentioned earlier the capacity factor of the turbine provides a valuable insight into potential areas for investment as well as areas where production could be optimised. As shown in Figure 8, the Eastern region has the highest turbine capacity factor of about 33% and one of the favourable locations for wind-based green hydrogen projects, followed by the Ashanti region with a capacity factor of 28%. The Savannah region recorded the lowest capacity factor of 6% due to the relatively low wind speed regime of the location compared to other regions in the countries.

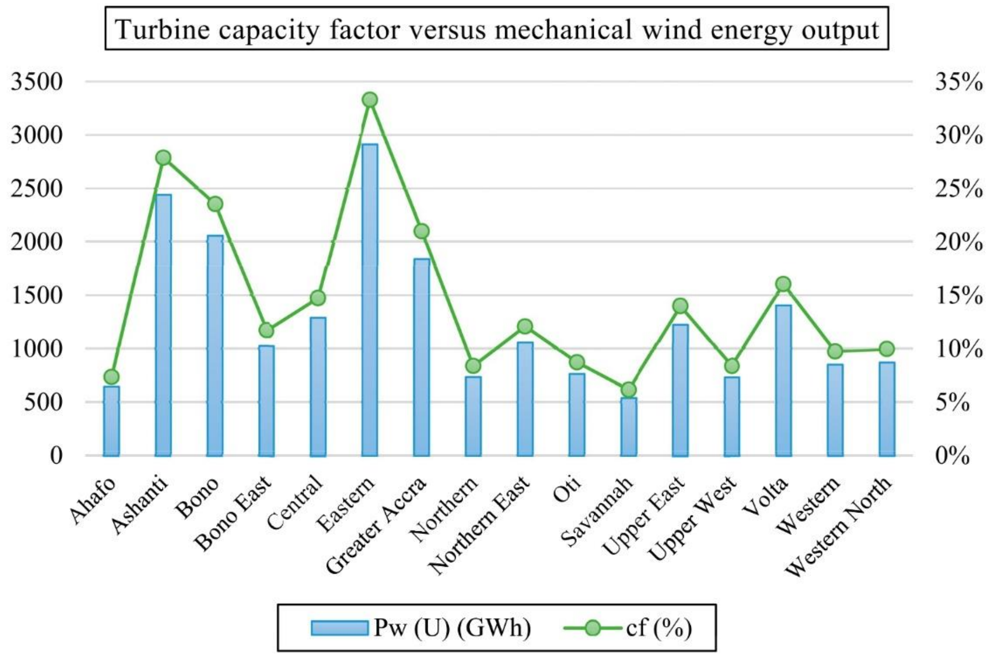


Figure 8. The wind turbine capacity factor with corresponding wind energy generated per region.

Figure 9 shows the geospatial model used to compute the wind-based green hydrogen technical potential. The model consists of four geo-processes. As mentioned earlier, the production of green hydrogen using wind involves two separate processes, the first process was to estimate the amount of wind energy that can be generated from the wind turbine conversion system (TP_WECS) using the raster calculator in ArcGIS for the calculations, and next process was to run the extracted wind energy through the electrolyser system to produce the green hydrogen (Wind_hydrogen_mass). Also as shown in (Equation 18), a spacing factor was also included to estimate how much potential can be generated when spacing of the wind turbine is considered. The spacing was only considered during the TP_WECS estimation which in effect also affected the amount of green hydrogen that can be produced by the electrolyser system.

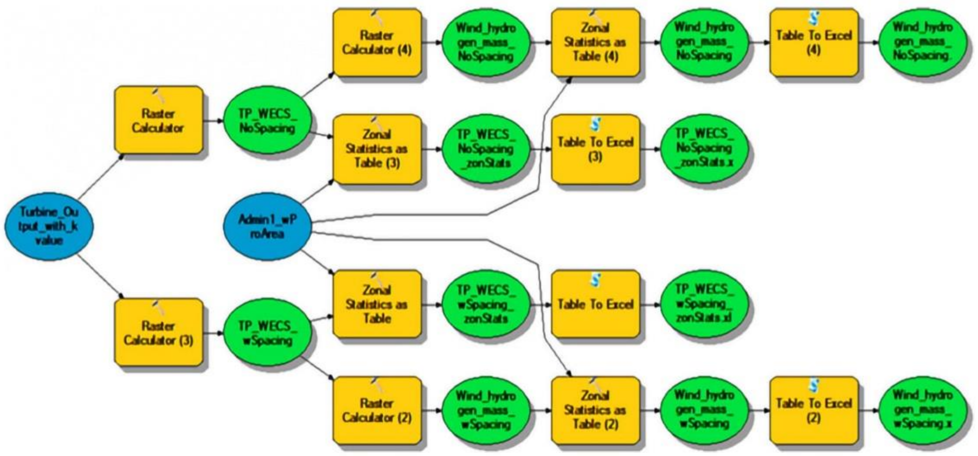


Figure 9. Wind-based green hydrogen technical potential model.

3.2.3. Potential for utility-scale system

Further, the study also tried to assess the viability of the green hydrogen project for a grid-connected or utility-scale system within the region. This was done by quantifying the generation capacities of the green hydrogen produced within a 20 km grid distance from the central power grid network, including the customer demand capacities within the 20 km grid distance by estimating the total number of people that live in this proximity distance within the region. As earlier discussed, this is in fulfilment of one of the key requirement for grid-connected system by the national electrification policy or standard of practice in Ghana (Asare-Addo 2022; Ghana – Action Plan for Sustainable Energy for All by 2030, 2012, 'SE4ALL-GHANA ACTION PLAN' 2012). The aim of this analysis is also to provide an overview of potential areas for green hydrogen project investment as well as to encourage renewable energy integration and diversification in the country' energy mix – that which is currently and predominantly fossil-based (Asare-Addo 2022; Energy Commission of Ghana 2020; Mary 2021; Odoi-Yorke et al. 2023). As shown in Figures 10 and 11 as well as Tables 2 and 3, the Greater Accra region has the highest energy demand customer base (100%) within the 20 km proximity threshold compared to the other regions and thus economically prudent to provide grid electrification to communities in this region. However, in terms of the green hydrogen generation capacities, the Upper West region had the largest capacity of ~719.93 Mt/year for the solar-based green hydrogen production without spacing considerations and about 71% of its population live within the potential for grid connection threshold (see Table 2). For the wind-based green hydrogen, the Eastern region still has the largest generation capacity of ~519.10 Mt/year

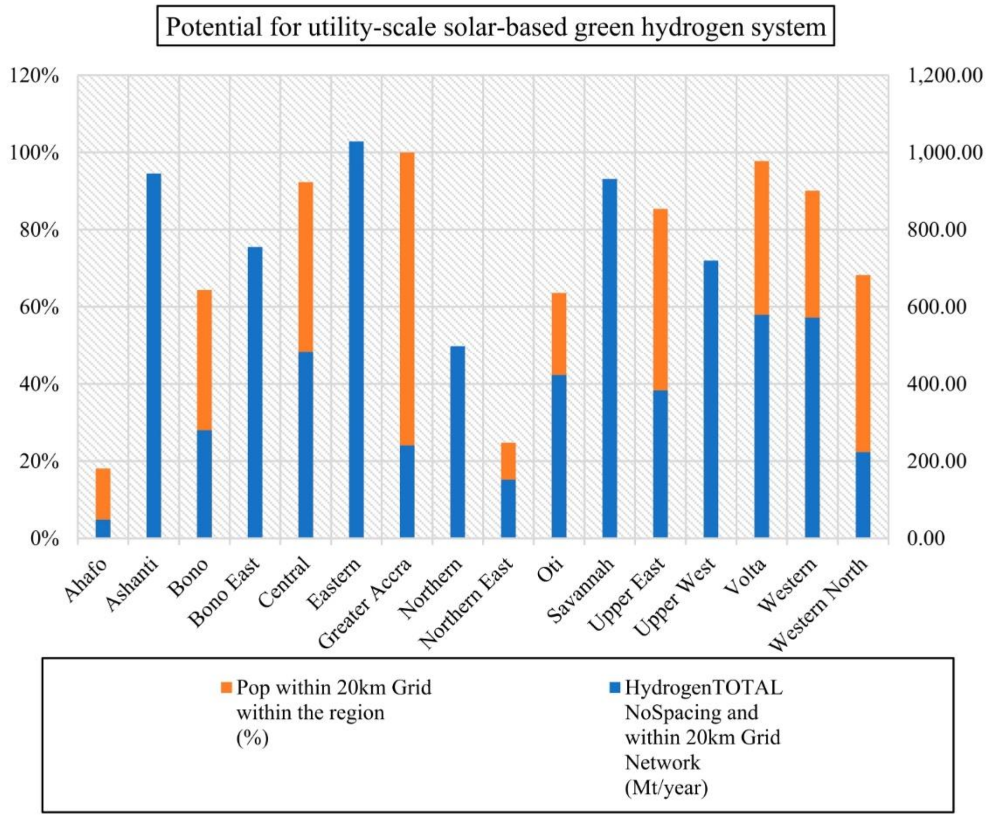


Figure 10. Potential for utility-scale solar-based green hydrogen.

with no spacing given the 20 km utility-scale distance threshold and has 98% of its population eligible for grid electrification as shown in Table 3. This therefore presents policy makers in Ghana with two sustainable energy intervention options: (i) the decision to prioritise investment in areas with larger generation capacities or, (ii) to prioritise investment in areas with higher energy demand customer base.

4. Discussion

As the global call to decarbonise energy systems continues and to help limit global warming to 1.5°C heightens (IPCC 2018), it has become increasingly important for governments to explore all sustainable alternative sources of energy available, which also includes the use of clean technologies in the production processes. The present study thus explores the potential of green hydrogen production in Ghana using solar and wind energy. The study applied the use of GIS techniques and PEM electrolysis process to assess the potential of the two selected renewable energy resources. This was done by first estimating the geographical potential which was to determine the area of land that were suitable and environmentally conducive to site the green hydrogen power plants. The Boolean method was applied in the GIS environment to delineate the suitable areas from restricted/ unsuitable areas. Thus, from the geographical potential evaluation, about 85% of the country's land area is ideal for green hydrogen production using solar and wind. Followed by the technical potential assessments of renewable resources used by first estimating the amount of energy that the conversion systems could generate from the solar PV power plant and from the wind turbine before converting the generated energy into green hydrogen through the water electrolysis process – a process which involves splitting water into hydrogen and oxygen, while emitting zero-carbon dioxide into the atmosphere. Results of the analysis show varying potentials across the various regions in Ghana. The assessment included estimating the amount of green hydrogen that the available land can produce with and without power plant spacing constraints. The present study went a step further to assess the potential of the green hydrogen power plants for a utility-scale or grid-connected systems, including an estimation of potential grid customers that could be serviced from the utility-scale green hydrogen power plants within each region in the country based on the 20 km distance from the grid network requirement for grid electrification as practiced in the country (Asare-Addo 2022; Ghana – Action Plan for Sustainable Energy for All by 2030, 2012, 'SE4ALL-GHANA ACTION PLAN' 2012), for which the Greater Accra region has the largest green hydrogen-grid customers (100%), and the lowest in the Ahafo region with ∼18% potential green hydrogen-grid customers. The aim of the utility-scale assessment was to provide insight into potential areas for investment. For green hydrogen using solar, the Savannah region showed the largest generation capacity of ∼1993.79 Mt/year. For the production of green hydrogen using wind, the Eastern region showed the most favourable location for green hydrogen projects using wind as the region recorded the highest capacity factor of 33%, and with a generation capacity of about ∼40,324.30 Tonnes/km^2/year while the Northern region recorded the largest potential of about 1298.41 Mt/year due to its geographical potential. Nationally, a total of ∼10,123.36 Mt of green hydrogen using wind can be produced annually with no spacing consideration and about 65.74 Mt/year when the wind turbines are spaced out given the geographical potential. For green hydrogen using solar, a total of ∼14,196.21 Mt can be produced annually in the country without spacing and ∼7098.11 Mt/year when spacing factor is considered.

5. Conclusion

The present study explored the potential of producing green hydrogen using solar and wind in Ghana by estimating the generating capacities at the national and regional levels in the country. Even though the country as at the end of 2022 does not have a hydrogen energy policy or any existing hydrogen initiative, opportunity to harness green hydrogen as part of the country's effort towards decarbonisation exist and even on a commercial base for export. Results of the assessment show that Ghana has good potential for green hydrogen production. A geographical and technical potential assessments were carried out for the two green hydrogen source by excluding all protected areas or conservation sites from the assessment. The remaining land areas were then estimated to determine how much land area is available regionally for the green hydrogen project. Results of the analysis show that, out of ∼239,428.99 km^2 total land area of the country, 85% is conducive for the selected green hydrogen sources. With the technical potential, the country can produce ∼14,196.21 Mt of green hydrogen using solar per annum, and ∼10,123.36 Mt/year of green hydrogen from wind.

From the assessment, it could be seen that areas with higher solar-based green hydrogen capacities were mainly recorded in the northern part of the country which presents a great opportunity even for grid-connected systems. However, the population densities in certain part of these regions may not meet the criteria for on-grid electrification and thus the decision to explore large-scale green hydrogen using solar especially, lies with the government which may require a revision of the NES to incorporate priority projects for large-scale deployment.

Integration of renewable energy into the power grid remains a challenge, therefore further research is needed on how to build grid resilience and its ability to transmit the green hydrogen to the residential end-user. Also, further studies on the implementation potential as well as how social conditioning of the location could impact the green hydrogen projects will be valuable.

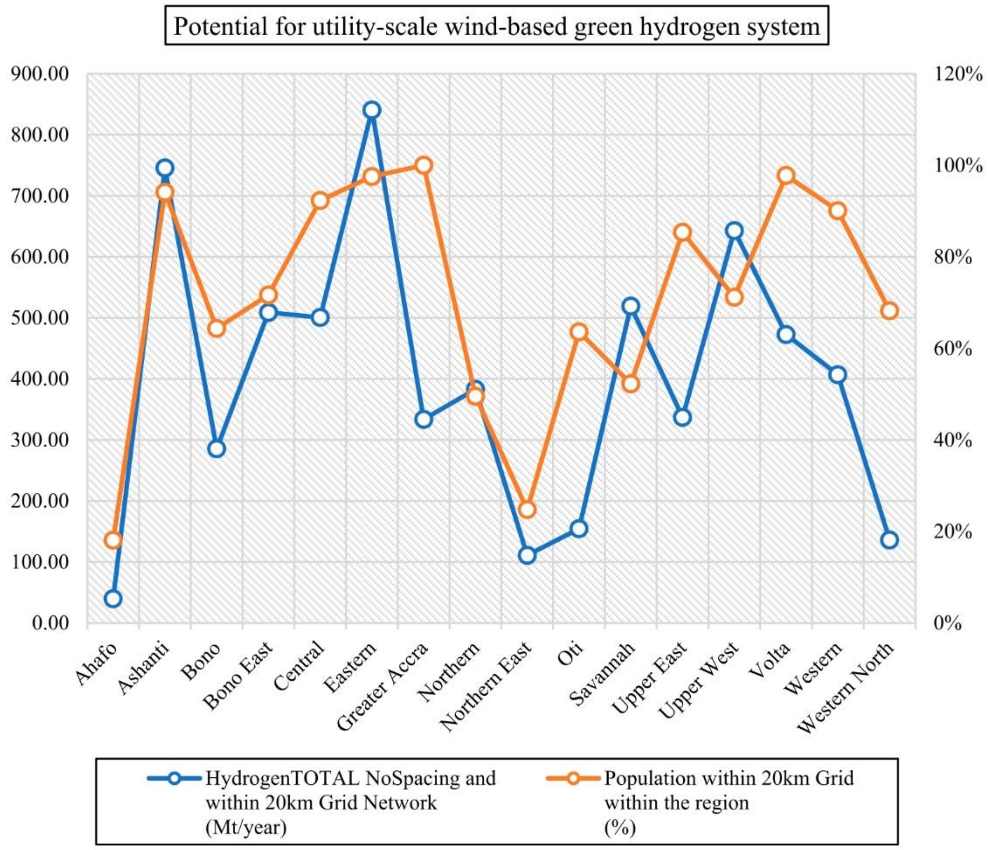


Figure 11. Potential for utility-scale wind-based green hydrogen.

Notes

1. Million tonnes.
2. Energy and electricity have been used interchangeably in this study to refer to same.
3. Wind speed cut-in is the point at which the turbine starts producing electricity from turning.
4. Wind speed cut-out is the maximum wind speed at which the turbine gets so fast and stands the risk of damage from operating further.

Acknowledgements

The author would like to thank this journal and its anonymous reviewers for peer-reviewing this paper. Special thanks to my academic supervisors for their guidance. Also grateful to family and friends for their continuous support and encouragement. *Credit author statement*: This article was independently written by the author. All datasets used in the study are open-sourced and have duly been referenced. The ArcGIS software licence used for this study was provided by the University of Flensburg.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

The authors acknowledge financial support by Land Schleswig-Holstein within the funding programme Open Access-Publikationsfonds.

References

Acakpovi, A., P. Adjei, N. Y. Asabere, R. A. Sowah, and D. M. Sackey. 2021. "Techno-Economic Evaluation of Hydrogen Fuel Cell Electricity Generation Based on Anloga (Ghana) Wind Regime." *International Journal of Energy Optimization and Engineering (IJEOE)* 10 (3): 47–69. https://doi.org/10.4018/IJEOE.2021070103.

Al-Orabi, A. M., M. G. Osman, and B. E. Sedhom. 2023. "Evaluation of Green Hydrogen Production Using Solar, Wind, and Hybrid Technologies Under Various Technical and Financial Scenarios for Multi-Sites in Egypt." *International Journal of Hydrogen Energy*. https://doi.org/10.1016/j.ijhydene.2023.06.218.

Ali, F., A. Bennui, S. Chowdhury, and K. Techato. 2022. "Suitable Site Selection for Solar-Based Green Hydrogen in Southern Thailand Using GIS-MCDM Approach." *Sustainability* 14 (11): 6597. https://doi.org/10.3390/su14116597.

Almutairi, K., S. S. Hosseini Dehshiri, S. J. Hosseini Dehshiri, A. Mostafaeipour, and K. Techato. 2022. "An Economic Investigation of the Wind-Hydrogen Projects: A Case Study." *International Journal of Hydrogen Energy* 47 (62): 25880–25898. https://doi.org/10.1016/j.ijhydene.2022.05.070.

Alrabie, K., and M. N. Saidan. 2018. "A Preliminary Solar-Hydrogen System for Jordan: Impacts Assessment and Scenarios Analysis." *International Journal of Hydrogen Energy* 43 (19): 9211–9223. https://doi.org/10.1016/j.ijhydene.2018.03.218.

Alshehri, F., V. G. Suárez, J. L. Rueda Torres, A. Perilla, and M. A. M. M. van der Meijden. 2019. "Modelling and Evaluation of PEM Hydrogen Technologies for Frequency Ancillary Services in Future Multi-Energy Sustainable Power Systems." *Heliyon* 5 (4): e01396. https://doi.org/10.1016/j.heliyon.2019.e01396.

Asare-Addo, M. 2022. "Optimal Techno-Economic Potential and Site Evaluation for Solar PV and CSP Systems in Ghana. A Geospatial AHP Multi-Criteria Approach." *Renewable Energy Focus* 41:216–229. https://doi.org/10.1016/j.ref.2022.03.007.

Ayodele, T. R., and J. L. Munda. 2019. "Potential and Economic Viability of Green Hydrogen Production by Water Electrolysis Using Wind Energy Resources in South Africa." *International Journal of Hydrogen Energy* 44 (33): 17669–17687. https://doi.org/10.1016/j.ijhydene.2019.05.077.

Ayodele, T. R., and A. S. O. Ogunjuyigbe. 2015. "Wind Energy Resource, Wind Energy Conversion System Modelling and Integration: A Survey." *International Journal of Sustainable Energy* 34 (10): 657–671. https://doi.org/10.1080/14786451.2013.855778.

Ball M, Weeda M. 2015. The Hydrogen Economy – Vision or Reality? *International Journal of Hydrogen Energy*. 40 (25):7903–7919. https://doi.org/10.1016/j.ijhydene.2015.04.032.

Ballo, A., K. K. Valentin, B. Korgo, K. O. Ogunjobi, S. N. Agbo, D. Kone, and M. Savadogo. 2022. "Law and Policy Review on Green Hydrogen Potential in ECOWAS Countries." *Energies* 15 (7): 2304. https://doi.org/10.3390/en15072304.

Berrada, A., and M. A. Laasmi. 2021. "Technical-Economic and Socio-Political Assessment of Hydrogen Production from Solar Energy." *Journal of Energy Storage* 44:103448. https://doi.org/10.1016/j.est.2021.103448.

Bhandari, R. 2022. "Green Hydrogen Production Potential in West Africa – Case of Niger." *Renewable Energy* 196:800–811. https://doi.org/10.1016/j.renene.2022.07.052.

Bhaskar, P., and T. Stehly. 2021. *Technology Innovation Pathways for Distributed Wind Balance-of-System Cost Reduction*. Golden, CO: National Renewable Energy Lab. (NREL). NREL/TP-5000-77452. https://www.osti.gov/biblio/1776704/.

Boudries, R. 2016. "Techno-economic Assessment of Solar Hydrogen Production Using CPV-Electrolysis Systems." *Energy Procedia* 93:96–101. https://doi.org/10.1016/j.egypro.2016.07.155.

Dagdougui, H., A. Ouammi, and R. Sacile. 2011. "A Regional Decision Support System for Onsite Renewable Hydrogen Production from Solar and Wind Energy Sources." *International Journal of Hydrogen Energy* 36 (22): 14324–14334. https://doi.org/10.1016/j.ijhydene.2011.08.050.

Energy Commission of Ghana. 2019. Ghana Renewable Energy Master Plan.

Energy Commission of Ghana. 2020. National Energy Statistics: 2000 - 2019.

Energy Commission of Ghana. 2021. Energy Outlook for Ghana: Demand and Supply Outlook. 2021.

Esri. 2016. Boolean Or – Help | ArcGIS for Desktop. January 26, 2016. Accessed March 1, 2023. https://desktop.arcgis.com/en/arcmap/10.3tools/spatial-analyst-toolbox/boolean-or.htm.

Esteves, N. B., A. Sigal, E. Leiva, C. R. Rodríguez, F. Cavalcante, and L. C. de Lima. 2015. "Wind and Solar Hydrogen for the Potential Production of Ammonia in the State of Ceará – Brazil." *International Journal of Hydrogen Energy* 40 (32): 9917–9923. https://doi.org/10.1016/j.ijhydene.2015.06.044.

Gallardo, F. I., A. Monforti Ferrario, M. Lamagna, E. Bocci, D. Astiaso Garcia, and T. E. Baeza-Jeria. 2021. "A Techno-Economic Analysis of Solar Hydrogen Production by Electrolysis in the North of Chile and the Case of Exportation from Atacama Desert to Japan." *International Journal of Hydrogen Energy* 46 (26): 13709–13728. https://doi.org/10.1016/j.ijhydene.2020.07.050.

Gaur, A., and G. N. Tiwari. 2013. "Performance of Photovoltaic Modules of Different Solar Cells." *Journal of Solar Energy* 2013: 1–13. https://doi.org/10.1155/2013/734581.

Genç, G., M. Çelik, and M. S. Genç. 2012. "Cost Analysis of Wind-Electrolyzer-Fuel Cell System for Energy Demand in Pınarbaşı-Kayseri." *International Journal of Hydrogen Energy* 37 (17): 12158–12166. https://doi.org/10.1016/j.ijhydene.2012.05.058.

Gerbo, A., K. V. Suryabhagavan, and T. K. Raghuvanshi. 2022. "GIS-Based Approach for Modeling Grid-Connected Solar Power Potential Sites: A Case Study of East Shewa Zone, Ethiopia." *Geology, Ecology, and Landscapes* 6 (3): 159–173. https://doi.org/10.1080/24749508.2020.1809059.

Action Plan for Sustainable Energy for All by 2030, 2012, 'SE4ALL-GHANA ACTION PLAN', viewed 5 April 2023, from http://energycom.gov.gh/files/SE4ALL-GHANA%20ACTION%20PLAN.pdf

Global Solar Atlas. 2023. "Global Solar Atlas 2.0, a free, web-based application is developed and operated by the company Solargis s.r.o. on behalf of the World Bank Group, utilizing Solargis data, with funding provided by the Energy Sector Management Assistance Program (ESMAP). For additional information." February 28, 2023. Accessed 29 March, 2023. https://globalsolaratlas.info/map?c=7.972198,-1.032715,7&r=GHA.

Global Wind Atlas. 2023. Global Wind Atlas 3.0, a free, web-based application developed, owned and operated by the Technical University of Denmark (DTU). The Global Wind Atlas 3.0 is released in partnership with the World Bank Group, utilizing data provided by Vortex, using funding provided by the Energy Sector Management Assistance Program (ESMAP). For additional information. October 3. Accessed March 10, 2023. https://globalwindatlas.info/en/area/Ghana.

Gouareh, A., N. Settou, A. Khalfi, B. Recioui, B. Negrou, S. Rahmouni, and B. Dokkar. 2015. "GIS-Based Analysis of Hydrogen Production from Geothermal Electricity Using CO_2 as Working Fluid in Algeria." *International Journal of Hydrogen Energy* 40 (44): 15244–15253. https://doi.org/10.1016/j.ijhydene.2015.05.105.

Gupta, N. 2016. "A Review on the Inclusion of Wind Generation in Power System Studies." *Renewable and Sustainable Energy Reviews* 59:530–543. https://doi.org/10.1016/j.rser.2016.01.009.

Herdem, M. S., D. Mazzeo, N. Matera, C. Baglivo, N. Khan, P. M. Congedo, and M. G. De Giorgi. 2023. "A Brief Overview of Solar and Wind-Based Green Hydrogen Production Systems: Trends and Standardization." *International Journal of Hydrogen Energy*. https://doi.org/10.1016/j.ijhydene.2023.05.172.

Hoogwijk, M., B. de Vries, and W. Turkenburg. 2004. "Assessment of the Global and Regional Geographical, Technical and Economic Potential of Onshore Wind Energy." *Energy Economics* 26 (5): 889–919. https://doi.org/10.1016/j.eneco.2004.04.016.

IEA (International Energy Agency). 2021. Global Hydrogen REVIEW 2021.

IEA (International Energy Agency). 2023. "Solar PV – Analysis - IEA." August 2. Accessed February 8, 2023. https://www.iea.org/reports/solar-pv.

International Renewable Energy Agency. 2014. *Estimating the Renewable Energy Potential in Africa: A GIS-Based Approach*. IRENA, viewed 18 July 2023, from https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2014/IRENA_Africa_Resource_Potential_Aug2014.pdf.

IPCC. 2018. Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.

Kakoulaki, G., I. Kougias, N. Taylor, F. Dolci, J. Moya, and A. Jäger-Waldau. 2021. "Green Hydrogen in Europe – A Regional Assessment: Substituting Existing Production with Electrolysis Powered by Renewables." *Energy Conversion and Management* 228:113649. https://doi.org/10.1016/j.enconman.2020.113649.

Karayel, G. K., N. Javani, and I. Dincer. 2022. "Green Hydrogen Production Potential for Turkey with Solar Energy." *International Journal of Hydrogen Energy* 47 (45): 19354–19364. https://doi.org/10.1016/j.ijhydene.2021.10.240.

Karayel, G. K., N. Javani, and I. Dincer. 2023. "Green Hydrogen Production Potential in Turkey with Wind Power." *International Journal of Green Energy* 20 (2): 129–138. https://doi.org/10.1080/15435075.2021.2023882.

Koko, S. P. 2022. "Optimal Battery Sizing for a Grid-Tied Solar Photovoltaic System Supplying a Residential Load: A Case Study Under South African Solar Irradiance." *Energy Reports* 8:410–418. https://doi.org/10.1016/j.egyr.2022.02.183.

Lantz, E., B. Sigrin, M. Gleason, R. Preus, and I. Baring-Gould. 2016. *Assessing the Future of Distributed Wind: Opportunities for Behind-the-Meter Projects*. Golden, CO: National Renewable Energy Lab. (NREL). NREL/TP-6A20-67337. https://www.osti.gov/biblio/1333625/.

Leiblein, J., K. Bär, F. Graf, C. Hotz, and F. Mörs. 2021. "Techno-Economic Analysis of Green Hydrogen Production from Solar Energy in Mena and Transport to Central Europe." International Solar Energy Society.

Liu, B., X. Ma, J. Guo, H. Li, S. Jin, Y. Ma, and W. Gong. 2023. "Estimating Hub-Height Wind Speed Based on a Machine Learning Algorithm: Implications for Wind Energy Assessment." *Atmospheric Chemistry and Physics* 23 (5): 3181–3193. https://doi.org/10.5194/acp-23-3181-2023.

Mackenzie, W. 2019. "The Future for Green Hydrogen." Accessed December 28, 2022. https://www.woodmac.com/news/editorial/the-future-for-green-hydrogen/.

Manwell, J. F., J. G. McGowan, and A. L. Rogers. 2009. "Wind Energy Explained: Theory, Design and Application." In *Anthony Rogers*, edited by J. F. Manwell and J. G. McGowan, 2nd ed., 33–65. Chichester: John Wiley.

Mary, A.-A. 2021. "Geospatial Mapping of Micro-Wind Energy for District Electrification in Ghana." *Energy* 225:120217. https://doi.org/10.1016/j.energy.2021.120217.

Messaoudi, D., N. Settou, B. Negrou, and B. Settou. 2019. "GIS Based Multi-Criteria Decision Making for Solar Hydrogen Production Sites Selection in Algeria." *International Journal of Hydrogen Energy* 44 (60): 31808–31831. https://doi.org/10.1016/j.ijhydene.2019.10.099.

Nematollahi, O., P. Alamdari, M. Jahangiri, A. Sedaghat, and A. A. Alemrajabi. 2019. "A Techno-Economical Assessment of Solar/Wind Resources and Hydrogen Production: A Case Study with GIS Maps." *Energy* 175:914–930. https://doi.org/10.1016/j.energy.2019.03.125.

OCHA & Humanitarian Data Exchange. 2021. "Ghana - Subnational Administrative Boundaries." Accessed 2023. https://data.humdata.org/dataset/cod-ab-gha.

Odoi-Yorke, F., T. F. Adu, B. C. Ampimah, and L. Atepor. 2023. "Techno-Economic Assessment of a Utility-Scale Wind Power Plant in Ghana." *Energy Conversion and Management: X* 18:100375. https://doi.org/10.1016/j.ecmx.2023.100375.

Okonkwo, P. C., E. M. Barhoumi, I. B. Mansir, W. Emori, and P. C. Uzoma. 2022. "Techno-Economic Analysis and Optimization of Solar and Wind Energy Systems for Hydrogen Production: A Case Study." *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects* 44 (4): 9119–9134. https://doi.org/10.1080/15567036.2022.2129875.

Okunlola, A., M. Davis, and A. Kumar. 2022. "The Development of an Assessment Framework to Determine the Technical Hydrogen Production Potential from Wind and Solar Energy." *Renewable and Sustainable Energy Reviews* 166:112610. https://doi.org/10.1016/j.rser.2022.112610.

Olateju, B., A. Kumar, and M. Secanell. 2016. "A Techno-Economic Assessment of Large Scale Wind-Hydrogen Production with Energy Storage in Western Canada." *International Journal of Hydrogen Energy* 41 (21): 8755–8776. https://doi.org/10.1016/j.ijhydene.2016.03.177.

Posso, F., J. Sánchez, J. L. Espinoza, and J. Siguencia. 2016. "Preliminary Estimation of Electrolytic Hydrogen Production Potential from Renewable Energies in Ecuador." *International Journal of Hydrogen Energy* 41 (4): 2326–2344. https://doi.org/10.1016/j.ijhydene.2015.11.155.

Posso, F., and J. Zambrano. 2014. "Estimation of Electrolytic Hydrogen Production Potential in Venezuela from Renewable Energies." *International Journal of Hydrogen Energy* 39 (23): 11846–11853. https://doi.org/10.1016/j.ijhydene.2014.06.033.

Rahmouni, S., B. Negrou, N. Settou, J. Dominguez, and A. Gouareh. 2017. "Prospects of Hydrogen Production Potential from Renewable Resources in Algeria." *International Journal of Hydrogen Energy* 42 (2): 1383–1395. https://doi.org/10.1016/j.ijhydene.2016.07.214.

Rahmouni, S., N. Settou, B. Negrou, and A. Gouareh. 2016. "GIS-based Method for Future Prospect of Hydrogen Demand in the Algerian Road Transport Sector." *International Journal of Hydrogen Energy* 41 (4): 2128–2143. https://doi.org/10.1016/j.ijhydene.2015.11.156.

Simpson, J. G., and E. Loth. 2022. "Super-rated Operational Concept for Increased Wind Turbine Power with Energy Storage." *Energy Conversion and Management: X* 14:100194. https://doi.org/10.1016/j.ecmx.2022.100194.

Sunarso, A., K. Ibrahim-Bathis, S. A. Murti, I. Budiarto, and H. S. Ruiz. 2020. "GIS-Based Assessment of the Technical and Economic Feasibility of Utility-Scale Solar PV Plants: Case Study in West Kalimantan Province." *Sustainability* 12 (15): 6283. https://doi.org/10.3390/su12156283.

Topriska, E., M. Kolokotroni, Z. Dehouche, D. T. Novieto, and E. A. Wilson. 2016. "The Potential to Generate Solar Hydrogen for Cooking Applications: Case Studies of Ghana, Jamaica and Indonesia." *Renewable Energy* 95:495–509. https://doi.org/10.1016/j.renene.2016.04.060.

Touili, S., A. Alami Merrouni, A. Azouzoute, Y. El Hassouani, and A. Amrani. 2018. "A Technical and Economical Assessment of Hydrogen Production Potential from Solar Energy in Morocco." *International Journal of Hydrogen Energy* 43 (51): 22777–22796. https://doi.org/10.1016/j.ijhydene.2018.10.136.

World Bank. 2023a. Access to Electricity (% of population) - Ghana | Data. July 4. Accessed April 7, 2023. https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS?locations=GH.

World Bank. 2023b. Tracking SDG 7 – The Energy Progress Report 2022. July 4. Accessed April 7, 2023. https://www.worldbank.org/en/topic/energy/publication/tracking-sdg-7-the-energy-progress-report-2022.

Yodwong, B., D. Guilbert, M. Phattanasak, W. Kaewmanee, M. Hinaje, and G. Vitale. 2020. "AC-DC Converters for Electrolyzer Applications: State of the Art and Future Challenges." *Electronics* 9 (6): 912. https://doi.org/10.3390/electronics9060912.

Yushchenko, A., A. de Bono, B. Chatenoux, M. K. Patel, and N. Ray. 2018. "GIS-Based Assessment of Photovoltaic (PV) and Concentrated Solar Power (CSP) Generation Potential in West Africa." *Renewable and Sustainable Energy Reviews* 81:2088–2103. https://doi.org/10.1016/j.rser.2017.06.021.