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Electric energy generation from small-scale solar and wind power in Brazil: The influence of location, area and shape

Alan Emanuel Duailibe Ribeiro*, Maurício Cardoso Arouca, Daniel Moreira Coelho

Energy Planning Program (PPE), Institute Graduate School and Research in Engineering at the Federal University of Rio de Janeiro (COPPE/UFRJ), Bloco C, Sala C-211, C.P. 68565, Cidade Universitária, Ilha do Fundão, CEP 21945-970, Rio de Janeiro, Brazil

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ABSTRACT

Power production from renewable sources is identified as one of the tools to attain sustainable development in economic and social terms in Brazil. Awareness of how to prioritize renewable energy sources and technologies becomes increasingly important. Solar and wind energy have been highlighted in this context as being clean, safe and also relatively mature technologies. In addition, they are also renowned for having great energy potential and allowing different mounting options for energy harvesting systems. This article seeks to contribute to the knowledge of the effects that the key attributes, location, area and shape, of a site can have on the potential of renewable generation. In order to incorporate these attributes into an integrated analysis, a comparison method is developed and subsequently applied in a case study for two Brazilian cities. Results indicate that the amount of energy obtained by a given power generation system can undergo large variations depending on the characteristics of attributes such as site location, area and shape. This variation may ultra-pass 200%, in some cases, which demonstrates the importance of a better understanding of the role of these attributes in determining energy production.

1. Introduction

Brazil is the largest country in South America and the fifth largest in the world, with an area of 8.5 million km^2 and a population of approximately 191 million people, IBGE census [1]. The electricity consumption attained 475.1 TWh in 2014 and is forecasted to grow at 3.9% per year until 2018 [2,3]. The Brazilian production and transmission of electricity is based on a hydrothermal system, with a strong predominance of hydroelectric plants.

Historically, Brazil has an energy matrix with a large share of renewables [4]. In 2013 79.3% of internal electricity power supply derive from renewables with 64.9% coming from hydraulic generation [5]. With increasing environmental restrictions for the construction of new hydroelectric plants [6,7], particularly in the Amazon, the participation of non-renewable sources has grown in recent years. One evidence is an increase of 20% in greenhouse gases emissions in the electricity sector [8].

A strategy to strengthen the participation of renewable energy sources beside hydropower dams in Brazil's power matrix, as well as to reduce greenhouse gas emissions, is to encourage the use of wind and solar power at large, medium and small scales. It is known that this action is viewed by society as a positive alternative to support economic and social development [9,10]. It is noteworthy that electricity generation at small scale is increasing in Brazil, particularly since 2013, due to a resolution of the Brazilian regulatory agency ANEEL [11,12]. The resolution establishes the regulatory framework for access of distributed microgeneration (less or equal to 100 kW) and minigeneration (more than 100 kW or equal or less than 1 MW) to the Brazilian power distribution systems.

The article presents an analysis of the great influence that the attributes (i) location; (ii) area and (iii) shape have on the potential of electricity generation by small-scale renewable sources, in particular solar photovoltaic and wind energy. The location attribute is commonly expressed by the geographic coordinates of a point to serve as a reference site within its topographic boundaries. The position of the site on the earth's surface determines the availability of natural resources that may be used for power generation. According to Van de Walle [13], the attribute area is the two-dimensional space that characterizes the site within a region, that is, a dimensional number (m^2) expressing the size of the site. The shape attribute corresponds to the geometric feature of its outline, i.e., the limiting outward line, which gives it a particular

* Corresponding author.
E-mail address: aedr@ppe.ufrj.br (A.E.D. Ribeiro).

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appearance.

Thus, two sites with the same area and geometric shape but with different locations, or two sites with different shape and/or area but with the same location hardly have the same energy potential. Furthermore, the area influences the type of technology that can be used in the site, while the shape determines the manner in which the technologies can be arranged or installed at the site. Therefore, area and shape affect the energy amount that may be generated on the site. The knowledge about the influence of these parameters is of great importance, as it helps in the optimization of the energy amount to be generated.

In international literature, the effects of the three attributes are usually studied in isolation. This study explains the same effects simultaneously, integrating them in a method; which identifies the impact that each of these parameters causes on the energy potential of a site.

Studies are available in literature that define the location, forms of installation methods to estimate every yields. The following case studies show different methods for these purposes. A method based on a geographic information system for the installation of a rooftop photovoltaic systems on a university campus in Arizona (USA) was presented by Kucuksari et al. [14]. In Ghadimi et al. [15] a study was conducted applying the topographic maps method and site visits. They aim at finding the best location of micro hydropower plants in remote areas in the Lorestan province in Iran. In his article, San Cristóbal [16] develops a goal programming method based on multi-sink networks to deploy five plants of renewable energy (wind, solar, hydroelectric and biomass) in Cantábria (Spain). To estimate the electricity produced by photovoltaic power systems integrated construction (BIPV), Massa-Bote e Caamaño-Martín [17] present a method based on a combination of incident radiation on the surface of the photovoltaic system and an estimation of the generated power that considers loses due to shading. Adelaja et al. [18] estimate the energy generated in systems with wind turbine technologies of horizontal axis and photovoltaic panels in abandoned industrial areas in Michigan (USA), the method considers the spacing between turbines and tilt angle of PV panels. Yunna and Geng [19] develop a methodology for selection of sites based on multi-criteria decision-making AHP model emphasizing not only the rankings of alternatives within the scope but also the rankings of alternatives in the sub-goals and evaluation attributes. This framework aims to help project managers to analyze the advantages and disadvantages of alternative sites, so that the probability of errors in decision-making may decrease.

Review articles also address those issues: Serrano González et al. [20] carry out a review of design solutions on wind farms, where it is stated that the first step is the choice of location. Two methodological trends were identified in the optimization process for siting wind turbines. The first is the use of economic optimization model of power generation algorithms. The second is the development of realistic models of the economic behavior of the wind farm. Mecibah et al. [21] present a review of about 100 optimization works of hybrid and grid-connected photovoltaic systems. The methods used are based on time series data of solar energy at room temperature and the wind conditions in available locations. These methodologies also calculate the angle of inclination of the panels and other system components. A review of several articles by Grassi et al. [22], aims to assess the performance of the photovoltaic system and day lighting system in sustainable buildings. The methodology to measure the efficiency of each system, considers aspects such as the selection of the type of panel used, the orientation of the building, the installation location, the area of the installation, and the tilt angle. However, Fadaee and Radzi [23] provides an overview of multi-objective methods using evolutionary algorithms to solve optimization problems with respect to the positioning, sizing, design, planning and control, in order to increase reliability of renewable energy hybrid systems in remote areas. Herbert et al. [24] reviews some factors (environmental and network integration) and techniques (resource assessment and improvement of wind turbine performance) to consider the installation of wind turbines. The study presented by Mcwilliam et al. [25] pursues to deliver a simple tool for preliminary activities capable to arrange a project of large scale wind-farms. It uses several mathematical models and the province of Alberta (Canada) as a case study. The algorithm is designed to find the setting that produces electricity at minimal cost. Many economic and regulatory scenarios are used.

Articles that introduce generic methodologies include the following: The use of a generic algorithm, to find the optimal position of wind turbines in wind farms, presented by Grady et al. [26], considers three wind conditions and the area of the park, and applies the methodology in sites with square shape. Kusiak and Song [27], similar to what is shown by Ref. [26] use a generic algorithm to determine the layout of the wind park, highlights the influence of land roughness and the use of same sized turbines, and propose that all the turbines are placed in a space in a circular way. The model also considers energy losses due to the wake effect created by the turbines. In his paper Grossmann et al. [28], presents a method of optimizing generation and storage of solar energy, which aims to reduce the phenomenon of intermittency in generation. To do so, he proposes the construction of a network of solar plants spread across all regions of the world. The approach optimizes two aspects, first the selection of sites in the network and second, the size, the generation and the storage capacity of each location. Lee et al. [29] in his article proposes a methodology to select properly wind farms, based on the decision-making model AHP multi-criteria with BCOR, characterized by doing pairwise comparisons between the criteria used, considering benefits (B), opportunities (O), cost (C) and hazards (R) of each alternative. Similarly, Chen et al. [30]add the tools of Fuzzy logic, in order to take into account the subjectivity and vagueness, inherent in opinion of experts a methodology proposed by Ref. [29], for hybrid power generation, solar and wind systems.

In general, the reviewed articles use, mostly implicitly, the three studied attributes. However, they do not identify or quantify the effects that these attributes have on the calculation of renewable energy potential of a site.

In this article, the impact of these attributes is explained by a method that compares the energy generated at sites with different areas and shapes in two locations, using specific photovoltaic polycrystalline silicon panels and horizontal-axis wind turbine technologies, which are the most frequently used technologies in Brazil. This article is divided in four sections. Section 2 describes the applied method; the case study is shown in Section 3 with the results and the conclusion in Section 4.

2. Method

Fig. 1 shows an outline of the chosen method to introduce the effects of the key attributes of a site on the power generation potential. The method covers four stages.

In order to have a comparison between sites at the end of the method stage 4, it is important to consider that the sites show the same conditions (roughness, wind direction, the possibility of using the entire area of the site).

2.1. Stage 1 – site characterization

The first stage is to characterize the site observing location, area and shape of the site, i.e., latitude, longitude, altitude, natural