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Proposed method for contracting of wind-photovoltaic projects connected to the Brazilian electric system using multiobjective programming

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ABSTRACT

Owing to the wind and photovoltaic (PV) potential in Brazil, the country has recently seen increased exploration into the construction of wind-PV hybrid plants. However, as specific criteria for contracting this type of project have not yet been developed, this paper presents a model to assist the government in contracting projects that maximize the socioeconomic well-being of the Brazilian electricity sector. For this, multiobjective programming is used to simultaneously handle two objective functions—maximally reducing emission density and minimizing the levelized cost of electricity (LCOE)—with the aid of the mixture arrangement technique. In this respect, the optimization method called normal boundary intersection (NBI) is applied to solve the multiobjective problem and construct the Pareto frontier. Additionally, a metric based on the ratio between entropy and the global percentage error (GPE) is used to identify the optimal Pareto solution. The model was applied to determine optimal configurations for wind-PV powerplants in twelve Brazilian cities, and the results obtained reveal the capacity of the model to indicate the optimum configuration according to the wind and PV potential of each city.

1. Introduction

In recent decades, Brazil has implemented strategies to encourage the use of renewable energy sources (RES) in order to reduce the dependence of large hydroelectric plants on its energy matrix [1]. The rationing and blackouts that occurred in the country between 2001 and 2002 were a significant motivator for the government to mobilize and promote the use of new energy sources—especially RES [2]. Since then, the country has introduced sources such as wind, biomass, small hydroelectric power stations, and more recently, photovoltaic (PV) in incentive programs and incentive contract environments [3].

In 2014, low hydroelectric reservoir levels led to a jump in energy prices in the market which further reinforced discourse on the need to promote alternatives to hydroelectric dams in Brazil [4]. At the end of the same year, for the first time, PV energy participated in an auction, and in April 2015 an Alternative Source Auction—LFA—contracted three wind farms. Additionally, in 2015, there were the New Energy Auctions with the participation of wind energy, and the Reserve Energy Auctions with the participation of solar and wind energy [5]. These events signal the country's intention to intensify the use of these sources, which are capable of diversifying the energy matrix and increasing sustainability in the electric system.

Due to the wind and solar potential in the country, the use of hybrid generation from wind-PV plants is timely, and becoming a reality with the recent construction of several wind-PV power projects [6]. Trannin [7] points out that advantages of power generation from these hybrid systems include: complementarity of sources, since the wind regime is more intense at night, while the incidence of sun occurs during the day; economies of scale, reducing the average cost to companies that invest in both sources; and that only one environmental impact study is necessary for a project that uses both sources, which accelerates the environmental licensing process.

However, the two sources also have specific disadvantages. In the case of wind power, according to Fadigas [8], among some of the main

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disadvantages are: the visual pollution caused in the places where wind powerplants are installed; noise pollution due to the sound of the wind blowing on the blades; and the impact of aero generators on birds of the region—potential to cause death to animals that collide with the aero generators. Additionally, based on Ramanathan [9], it is observed that the wind and biomass plants occupy a significant area, and for this reason, the construction of wind powerplants can cause the de-characterization of the natural habitat where they are installed, increase land expenses, and limit the option of future enterprise expansion.

In relation to solar energy, the main disadvantages are: the lack of energy production at night [10]; technology still in the stage of maturation with the levelized cost of electricity (LCOE) still higher than that of other RES, such as wind and biomass [11]; and in places of medium to high latitudes, production falls sharply during the winter.

In this respect, an interesting alternative that combines the advantages of wind power and PV for the production of electricity, while reducing the impact of the disadvantages of each source, is the wind-PV hybrid system. In addition to being more reliable and less expensive [12], optimally sized hybrid generation projects maximize the potential of natural resources, such as sun and wind [13]. In many cases, a degree of complementarity among sources, the possibility of optimization of operating and investment costs, and the reduction of social and environmental impacts are pointed out. Based on these arguments, some generator agents have proposed specific energy auctions for the contracting of wind-PV hybrid plants, thereby seeking to expand the space for new projects, bypassing several constraints of the transmission system for wind energy and PV [6].

Considering that investors are beginning to show interest in wind and PV sources in the form of hybrid projects, it is important to develop mathematical models that guide the government in bidding processes aimed at contracts that use the two sources simultaneously. Thus, the present study aims to develop a method capable of assisting the government in the bidding process so as to contract grid-connected, wind-PV power generation projects that are optimally configured from the economic and socio-environmental perspectives.

To achieve this goal, multiobjective programming is used to guide the contracting of projects that simultaneously reduce CO_2 emissions per occupied area, as well as minimize the LCOE. Thus, LCOE modeling and CO_2 emission reduction were carried out using a mixture arrangement technique and, later, the normal boundary intersection (NBI) methodology was used to perform the multiobjective optimization of the functions in the study. The proposed method will be applied to analyze the best configuration for a hybrid plant in the following twelve Brazilian cities: Araripina, in Pernambuco (PE); Braganca Paulista, in the state of Sao Paulo (SP); Campo Grande, in Mato Grosso do Sul (MS); Jundiai, in the state of Sao Paulo (SP); Laguna, in Santa Catarina (SC); Macau, in Rio Grande do Norte (RN); Mineiros, in Goiás (GO); Montes Claros, in Minas Gerais (MG); Mossoro, in Rio Grande do Norte (RN); Parnaiba, in Piaui (PI); Rio Grande, Rio Grande do Sul (RS); and Xique-Xique, in Bahia (BA).

2. Multiobjective programming

Impacts of power generation projects have become increasingly critical, and project planning has become increasingly complex. Therefore, Oree et al. [14] argue that classic formulations, such as models that include cost minimization as a sole objective, are becoming less realistic, and it is necessary to consider more attributes in the energy planning process.

Models that aim only to minimize costs are free of conflict between two or more objectives and therefore the solution can be found when the function reaches its optimum. In this case, no special method is needed [15]. However, when the optimization problem encompasses more than one objective, the complexity increases because the objectives are functions of the same decision variables and conflict with each other [16]. In order to study the trade-off between conflicting objectives and explore the available options, it is necessary to formulate an optimization problem from methods capable of working with multiple objective functions. The following mathematical expression demonstrates a typical multiobjective optimization problem:

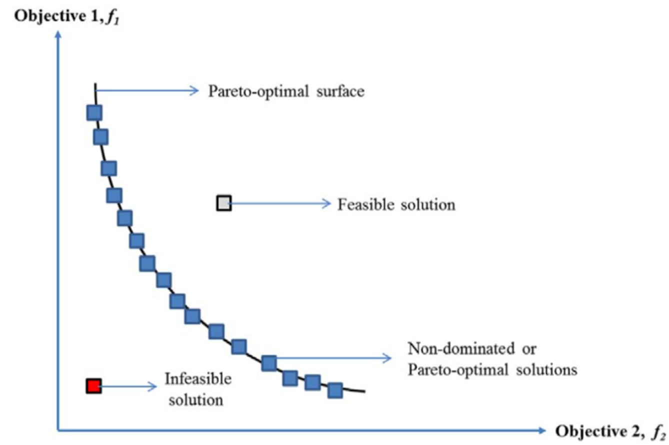

Fig. 1. Pareto frontier for a minimization problem with two objectives. Source: Oree, et al. [14].

$$\begin{aligned} &Min.\ F(x) = \{f_1(x), f_2(x), \ldots f_k(x)\}^T \\ &s.\ t.\ :\{x \in \mathbb{R}^n | g_r(x) \leq 0,\ r \in I,\ h_q(x) = 0,\ q \in J\} \end{aligned} \tag{1}$$

where: $F(x)$ is the vector of objective functions (f_i) consisting of k criteria, which are mutually conflicting; x is the vector of decision variables; g_r and h_q are the functions of restriction of inequality and equality, respectively; I and J are the index sets containing as many elements as inequality and equality constraints, respectively.

The models developed from these methods assist in identifying a satisfactory solution from a set of non-dominated, or Pareto-optimal solutions. In Fig. 1, the efficient frontier (or Pareto frontier) for a problem with two objectives is represented.

According to Shahraki and Noorossana [17], solution strategies for multiobjective problems can be divided into two methods: prioritization and agglutination. The first is the optimization of one goal, subject to constraints that involve the other goals. Among the examples of this solution strategy are: ε-method [15] and lexicographic programming [18]. The second is characterized by converting all objective functions into one, thereby reducing the original problem [19]. Among the main agglutination methods are: goal programming [20]; the global criterion method [15]; the weighted sum method [21]; and the NBI [22].

With regard to solving energy planning problems with optimization models, it is possible to find studies in the literature that similarly seek to propose new solutions. Initially, studies such as Park et al. [23], Kannan et al. [24], and Sirikum et al. [25] used formulations that included only cost minimization as the main objective. However, problems related to energy planning often involve multiple objectives that generally conflict with one another [26–28]. According to Aghaei et al. [29], the most common objectives in energy planning involve cost minimization, environmental impacts, and adequate system reliability.

Recently, the NBI method has been used in several studies to solve energy planning problems. Aghaei et al. [29] developed a multi-objective programming model from the NBI, aiming at power generation expansion planning that prioritizes the following objectives: minimization of costs and environmental impacts, as well as maximization of reliability. Vahidinasab and Jadid [30] formulated a model for the strategy of contracting generation projects for an electric system, taking into account the minimization of power flow (combined with coefficients that represent the emission of pollutants), maximization of individual return for investors, and physical constraints of power generation.

Izadbakhsh et al. [31] developed an optimization model to