A Hybrid Multi-Criteria Methodology for Solving the Sustainable Dispatch Problem

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Abstract: Wind energy is becoming an increasingly substantial component of many nations' energy portfolios. The intermittent nature of wind energy is traded off in a multi-objective sense against its environmental benefits when compared to conventional thermal energy sources. This gives rise to the multi-criteria sustainable dispatch problem considered in this paper. A relevant multi-objective model is formulated considering both environmental and economic criteria as well as ensuring adequate production levels. The techniques of weighted goal programming (WGP) and the progressive bounded constraint method (PBC) are combined in a novel manner in order to overcome computational challenges associated with the sinusoidal nature of the model. This allows the generation of a representative set of Pareto efficient solutions. The proposed methodology is demonstrated on a test set of relevant examples, and conclusions are drawn from both methodological and application perspectives. The results provide a quantification of the economic and environmental benefits of added wind power to a solely thermal system. However, a trade-off between the levels of economic versus environmental benefits gained is also demonstrated.

Keywords: wind energy; multi-objective optimization; weighted goal programming; progressive bounded constraint

1. Introduction

The wind power industry has undergone a period of substantial growth in recent decades. Initially, this involved wind farms being built onshore, but has more recently also involved the planning and operation of offshore wind farms as well. Attributes in the growth trend include larger turbines with a greater per turbine electricity production capacity and larger farms in terms of geographical area and number of turbines, particularly in the offshore case. In terms of geographic zones, wind energy can be seen as an increasingly global phenomenon, with Asian, North American, European, and South American countries represented in the top ten producers by installed capacity, and a global installed capacity of 651 GW by the end of 2019. With respect to this global growth, wind power can be seen as following a similar trend to that of other renewable energy sources, with particular growth seen in the solar [1] and biofuel [2] sectors. Other sources, such as wave and tidal [3], are at a more emergent phase of their technological lifecycle, but offer good future potential. Comparative analyses of renewable energy sources can be found in Lee and Chang [4] and Salim and Alsyouf [5].

The above growth highlights the need for the continued consideration of multiple sustainability dimensions in the global wind industry. There is a growing body of literature on the topic. The trade-offs between the key economic, environmental, social, and technical sustainability criteria for a range of decision-making situations can be analyzed using multiple-criteria decision-making (MCDM) methods. This can apply to a range of strategic and operational decision problems arising throughout the lifecycle of a wind farm. Recent works in this regard include that of Rehman et al. [6], who consider the location of onshore wind farms from a discrete set of alternatives. Seventeen underlying criteria across economic, environmental, social, and technical sustainability dimensions are considered, and the authors apply the Promethee MCDM methodology to investigate multiple criteria trade-offs and, hence, suggest optimal locations. Jones and Wall [7] also consider wind farm location with a discrete set of alternatives, but in the offshore context. Economic (life cycle costs), environmental (impact on locality), social (effects on other maritime users), and technical (power generated by season) sustainability goals are considered. The MCDM technique of goal programming is used to suggest optimal location strategies under different values of decision-maker importance assigned to the criteria. Konneh et al. [8] consider the place of wind energy in an enhanced sustainable energy portfolio for Sierra Leone. Economic (life cycle costs), technical (reliability, deficiency probability) and environmental (CO_2 emissions) criteria are considered. A multiple-objective particle swarm method is used to generate Pareto sets that illustrate the trade-offs between criteria. Akbari et al. [9] use the technique of Data Envelopment Analysis (DEA) to assess the efficiency of offshore wind farms in Northwestern Europe. Considering design aspects, De La Fuente et al. [10] use the Analytical Hierarchy Process to evaluate wind turbine tower designs. Economic (life cycle costs), environmental (material and energy consumption, CO_2 emissions), and social criteria (accident risk, visual perception, and patents generated) are considered.

The above works largely concentrate on strategic aspects of wind farm location and design. The methodology proposed in this paper focuses on the multi-criteria problem of effectively dispatching the electricity produced from wind farms when combined with conventional sources in a power grid network.

Considering dispatch problems specified in the literature, the single-objective economic dispatch problem with the inclusion of wind power aims to minimize the costs of wind power generation, which is related to weather factors, such as wind speed, which is a random variable. Thus, the model is stochastic because of the influence of wind behavior, which presents velocity variation over short time intervals. In models that analyze wind energy production, a Weibull probability distribution function is considered due to its ability to make wind predictions using relatively limited data [11]. The multi-objective sustainable (economic and environmental) dispatch problem for a traditional thermal generation system aims to minimize both the cost of fuels and the emission of pollutants that occur through the burning of fossil fuels, whilst at the same time meeting the operational constraints of the system. Hetzer, Yu, and Bhattarai [11] propose a combined thermal and wind economic dispatch model with the objective of minimizing the fuel costs of thermal plants and the costs of wind generation. System constraints include the fulfillment of demand and respecting the operating limits of both the thermal and wind generators. The consideration of the joint cost of thermal and wind generation and the focus solely on economic costs enable the authors to solve the model as a single objective problem. An explanation of some distinct cases related to the cost coefficients associated with these integrals, thus presenting the behavior of the wind and thermal generators in relation to their variation, is given in the paper. Güvenç and Kaymaz [12] also propose a thermal and wind economic dispatch model with the aim of minimizing thermal power fuel costs and wind generation costs whilst meeting a demand and considering the insertion of losses in the transmission of the electric power system. The model was solved by a COA (Coyote Optimization Algorithm), which is a recent heuristic algorithm based on population and swarm intelligence, where the main inspiration is coyote behavior. The results were compared with those obtained by GA (Genetic Algorithm) and PSO (Particle Swarm Optimization).

A multi-objective model is proposed in Qu et al. [13], which minimizes the economic and environmental functions of thermal generators. The wind generators are included in the model constraints, where the generation of thermal and wind units must cover the demand and the losses of power transmission, the reserve capacity of the system, and the production limits of thermal generators. The multi-objective evolutionary meta-heuristic NSGA-II (Non-dominated Sorting Genetic Algorithm II) is used, which is based on the concept of dominance and preservation of the solution curve diversity. Additionally used is the SMODE (summation-based multi-objective differential evolution) method, which is a heuristic method for solving multi-objective problems based on differential evolution algorithms.

A further multi-objective model approach is presented by Zhang et al. [14], which includes three objective functions: An economic function presented in Hetzer, Yu, and Bhattarai [11], which adds the cost function of thermal and wind generators, an environmental function, and a loss function in the transmission grid, where the constraints are related to energy balance and safety restrictions. The multi-objective problem is transformed into single-objective sub-problems, which are solved by a new approach of a differential evolution algorithm called GPBNI (generalized piecewise normal boundary intersection). A comparison of the GPBNI results with those of other works found in the literature is given.

Discussions regarding the modeling of trade-offs of environmental and economic sustainability issues in energy production are found in recent articles by Rajagopalan et al. [15], Zhu et al. [16], and Singh and Mishra [17]. According to Zhu et al. [16], wind energy production is more complicated to incorporate in an optimization problem because of its inherent stochasticity derived from wind randomness. One way to address the stochasticity of the problem is to turn it into an equivalent deterministic problem, as found in Yin and Zhao [18], which transforms this problem into a mixed integer programming problem. For multi-objective problems, one of the strategies relating to the inherent structure is to merge two objectives into a single objective function and solve the resulting model using the weighted sum method, as seen in El-Sehiemy, Rizk-Allah, and Attia [19].

Advancing upon the cited works above, this paper proposes a hybrid methodology that includes the sustainable criteria of the economic and environmental dispatch of thermal power and the economic dispatch of a wind farm. This results in a multi-objective model that simultaneously minimizes production costs and the emission of polluting gases. This is achieved whilst meeting a given production demand with the insertion of losses incurred in the transmission of the electricity in the power system and operational constraints of thermal and wind generators. The combination of these problems into a single model is termed the multi-objective wind–thermal economic and environmental dispatch problem (WTEEDP). Most of the works found in the literature that deal with WTEEDP do not use deterministic methods for its resolution and do not address the issue of environmental dispatch in its formulation, which are the objectives of this paper.

A further point of novelty is that the deterministic methodology proposed in this paper for the WTEEDP solution combines two multi-objective problem-solving methods: The progressive bounded constraints (PBC) method developed in Dos Santos et al. [20] and Gonçalves et al. [21], and the goal programming technique detailed in Jones and Tamiz [22]. Interior point methods, detailed, among others, in Mehrotra [23] and Bertsekas et al. [24] and available in Gams software, are used to solve the developed model. In the proposed model, the cost functions of thermal and wind dispatch are combined, as in Hetzer, Yu, and Bhattarai [11] and Güvenç and Kaymaz [12], hence ensuring that this problem has two distinct objectives and enabling the use of the above-mentioned multi-objective methods.

The PBC turns the original problem into a set of single-objective sub-problems, keeping one of the functions as the objective of the problem whilst converting the other objective function into upper and lower bounded constraints. It is hence iteratively used in order to determine an approximation of the Pareto optimal set of the problem. With sufficiently rigorously set target values, the goal programming technique also allows the determination of solutions to the problem that belong to the Pareto optimal

set. The weighted goal programming variant is used in this paper, which utilizes a set of weights determined by the levels of importance that the decision-maker gives to the minimization of unwanted deviations from the goal target values. Solving the goal programming model for multiple sets of weights enables the generation of a set of solutions that belong to the Pareto optimal set determined by the PBC method and that give a trade-off between the different underlying objectives. Thus, one technique is corroborated by the other and vice versa. Based on PBC and weighted goal programming, a new composite technique is hence proposed in this work, termed weighted goal programming with progressive bounded constraints (WGPPBC). This is necessary because of the difficulty presented in the resolution of a sine absolute value function that appears in the problem constraints.

This paper aims to show how the inclusion of wind turbines in the power generation system can produce new solutions that are Pareto efficient with respect to environmental impact and the cost of production whilst fulfilling the pre-established demand with consideration of losses. In comparison with a model that just includes thermal sources, this paper attempts to show that inclusion of wind turbines can, in some cases, improve both environmental impact and cost of production, thus improving the sustainability of the system. A further contribution of this work is in solving a multi-objective model that is stochastic in nature due to the use of a random variable describing the wind energy by utilizing a deterministic approach for its resolution, in contrast to the results found in the literature (e.g., Hetzer, Yu, and Bhattarai [11], Qu et al. [13], and Güvenç and Kaymaz [12]).

The main aims of this paper are (i) to quantify the level of environmental and economic benefit achieved by adding wind power units into a conventional thermal power system and (ii) to quantify any trade-offs that occur between environmental and economic gains when adding wind power units into a conventional thermal power system. Both aims (i) and (ii) are in the context of modeling the economic–environmental dispatch problem and link to wider concepts of enhancing the sustainability of power systems. The results should be of interest to planners of new or upgraded power systems, as well as governmental and private decision-makers needing to enhance the sustainability of their power systems.

The remainder of this work is divided and organized as follows: Section 2 presents the WTEEDP formulation, the economic and environmental objectives of thermal power generation, and the economic objective of the wind system, which is based on a Weibull probability distribution. The model has the insertion of valve loading points; hence, the treatment of the resulting modular terms in the economical objective of thermal generation is also addressed. Section 2.4 presents the progressive bounded constraint method (PBC), the weighted goal programming technique (WGP), and the WGPPBC technique used due to the sinusoidal function in the model. Section 3 presents the results obtained in the case for the WTEEDP in different instances of the power generation system. Finally, conclusions are drawn with respect to the proposed methodology and its application in Section 4.

2. The Mathematical Model

As detailed in the previous section, a sustainable dispatch model containing economic and environmental objectives is proposed in this paper. In the literature, the economic objective (*Fe*) is a quadratic and convex function (without the insertion of a loading valve point), defined as the summation of the cost function related to the fuel costs of each generator (Steinberg and Smith [25]).

The environmental impacts caused by thermal generators were not historically emphasized, as the economic issue was a priority in the production of thermal energy. However, with the increase in the emission of gases into the atmosphere, the need to use generators that caused less environmental damage arose, but their generation costs were higher. The environmental dispatch objective aims to reduce the emission of pollutants, hence considering the environmental conditions and emission reduction for a thermal energy generation system.

A wind farm dispatch model should consider production costs, which are currently low compared to other renewable energy sources. In addition, to be considered are the fulfillment of specific demand and the operational constraints of the wind generators according to their production limitations.

The economic objective of wind power generation (Fw) should incorporate the uncertainty of wind speed and, hence, the level of power generation. The cost of wind power production is hence composed of three different cost types: The linear cost (C_w), the penalty cost (C_p), and the reserve cost (C_r). These are, respectively, the cost associated directly with the amount of energy produced, the cost representing the difference between the available wind energy and the amount used, and the cost representing the uncertainty of the available wind energy generation being less than the planned level. Due to the aforementioned uncertainty in wind energy production, in this work, the penalty cost and reserve functions use a Weibull probability distribution in their formulation. Definitions regarding this function are based on Hetzer, Yu, and Bhattarai [11].

When inserting the losses in the transmission of the electricity of the power system, the Kron formula is used, which represents these losses through the B-coefficient matrix, where the generated power has to be enough to supply the demand as well as the system losses of transmission (Silva [26]).

2.1. Multi-Objective Wind–Thermal Economic and Environmental Dispatch Problem (WTEEDP)

The mathematical model formulated by modeling the above objectives and constraints is termed WTEEDP and is algebraically represented as:

$$Minimize \left\{ \sum_{j=1}^{m} Fe + \sum_{i=1}^{n} Fw, \sum_{j=1}^{m} Fa \right\} \tag{1a}$$

$$subject\ to\ \sum_{i=1}^{n} Pw_i + \sum_{j=1}^{m} Pt_j = D + L \tag{1b}$$

$$0 \leq Pw_i \leq Pw_i^{max} \tag{1c}$$

$$Pt_j^{min} \leq Pt_j \leq Pt_j^{max} \tag{1d}$$

in which:

(1a) is the bi-objective function of the problem.
(1b) is the constraint of meeting the demand of the power generation system.
(1c) is the constraint that imposes the power limitations of the wind power generators.
(1d) is the constraint that imposes the power limitations of the thermal generators.

The sustainability functions of the problem involving Fe, Fa, and Fw, expressed in (1a), are defined as:

Fe: Economic function of thermal plants, defined by:

$$Fe = \sum_{j=1}^{m} a_j P_{t_j}^2 + b_j P_{t_j} + cj + \mid e_j\ sen\ (f_j\ (P_{t_j}^{min} - P_{t_j}), \mid \tag{2}$$

where a_j, b_j, c_j, e_j, and f_j represent the coefficients of the economic function of the generating unit j. The absolute value term represented in (2) is associated with the effect of the valve loading points and transforms the objective function (2) into non-differentiable (at these points) and non-convex modular terms. This non-differentiability will be considered in Section 2.3.

Fa: Environmental function of the thermal plants, defined by:

$$Fa = \sum_{j=1}^{m} A_j P_{t_j}^2 + B_j P_{t_j} + C_j, \tag{3}$$

where A_j, B_j, and C_j are the values of the environmental function coefficients of the j generating unit.

Fw: Economic function of the wind farms, defined by:

$$Fw = C_w + C_p + C_r,$$

(4)

where C_w, C_p and C_r are respectively the linear, penalty, and reserve costs defined in Section 2.2, modeled as Weibull functions.

2.2. Economic Function of Wind Farms

The economic dispatch problem related to wind power energy aims to minimize the costs of wind power generation. As previously mentioned, this function will be stochastic due to the uncertain nature of wind speeds. The Weibull probability distribution is the most frequently used for checking wind speed frequency curves because of its simple graphical representation and its probability density function being a variant of Gamma probability distribution (Da Silva, Alves, and Cavalcanti [27], Gabriel Filho et al. [28], Al-Hasan and Nigmatullin [29], and Nascimento et al. [30]).

The resulting Weibull probability density function (pdf) is represented as:

$$fV(v) = \left(\frac{k}{c}\right) \left(\frac{v}{c}\right)^{k-1} exp\left(-\frac{v}{c}\right)^k \qquad 0 < v < \infty,$$

(5)

in which:

v: Wind speed.
c: Scale factor of a location (with unit of measure equal to wind speed).
k: Form factor of a location (dimensionless).

The c scale factor presented in (5) is directly related to the average speed and classifies the wind speed at the location where the wind farm is installed. The k form factor refers to the uniform distribution of the wind speed values and is known as the distribution inclination (Rocha et al. [31]).

The use of the function (5) in the wind power energy conversion system is given by the probability distribution function (PDF) in (6):

$$FV(v) = \int_v^0 fV(\Gamma)\, d\Gamma = 1 - exp\left(-\left(\frac{v}{c}\right)^k\right).$$

(6)

Due to the characteristics of wind speed, the distribution of wind farms in the wind energy conversion system (WECS) can be modeled as either a discrete or continuous distribution, with the continuous case utilized in this paper as described below. This is due to a linear transformation of the probability density function (5) to the wind speed (m/s), where an analysis is performed to determine the output power. Equations (7)–(9) show how speed wind variation determines the output power of generated energy.

$$w = 0 \qquad\qquad v < v_i \ e \ v > v_o$$

(7)

$$w = w_r\, \frac{(v - v_i)}{(v_r - v_i)} \qquad\qquad v_i \leq v \leq v_r$$

(8)

$$w = w_r \qquad\qquad v_r \leq v \leq v_o$$

(9)

Equations (7)–(9) assume that some wind speed limiters are required for the wind power generator to produce energy. Initially, we do not have an output power of energy generated, because in order for the turbines to operate, it is necessary that the wind reaches an initial speed (v_i). When the wind speed is between the cut-in wind speed (v_i) and the rated wind speed (v_r), this relationship is linear, where the generated power gradually increases until it reaches its rated power (w_r). The v_r speed is

determined by the nominal speed because of the output power (w_r) that represents the wind generator capacity limit. The rated power remains constant between the rated wind speed (v_r) until it reaches the cut-off speed (v_o), which serves to stop the wind generator energy production in order to avoid structural damage to turbines. The output power (w) for the WECS is, therefore, a mixed random variable, as it is continuous in the wind speed range for $v_i \leq v \leq v_r$ and a discrete variable in the wind speed ranges for $v < v_i$, $v > v_o$, and $v_r \leq v \leq v_o$. The representation of this function for the discrete case, not explored in this paper, can be seen in Hetzer, Yu, and Bhattarai [11].

To use the function (6) to determine the wind speed distribution, a transformation of this distribution is required to make the WECS compatible, i.e., the function is transformed to no longer depend on the incidence of wind speed—it considers only its expression in relation to the power of wind generators. The Weibull probability distribution function for the WECS is hence transformed in order to be represented as (10):

$$fW(w) = \frac{k\,l\,v_i}{c} \left(\frac{(1 + \rho\,l)\,v_i}{c} \right)^{k-1} exp \left(- \left(\frac{(1 + \rho\,l)\,v_i}{c} \right)^k \right),$$ (10)

in which:

$l = \dfrac{(v_r - v_i)}{v_i}$: Is the ratio of linear range of wind speed to cut-in wind speed.

$\rho = \dfrac{w}{w_r}$: Is the ratio of wind power output to rated wind power.

The WECS economic function, defined in (4), has the function-related penalty cost and reserve functions (10). Thus, the economic function of wind farms (Fw) is given by the sum of the linear cost (C_w), penalty cost (C_p), and reserve cost (C_r), defined as:

$$C_w(P_{w_i}) = d_i \cdot P_{w_i}$$ (11)

$$C_p\,(P_{w_i}) = k_{p_i} \left(\int_{P_{w_i}}^{w_{r_i}} w\,fW(w)\,dw - P_{w_i} \int_{P_{w_i}}^{w_{r_i}} fW(w)\,dw \right)$$ (12)

$$C_r\,(P_{w_i}) = k_{r_i} \left(P_{w_i} \int_0^{P_{w_i}} fW(w)\,dw - \int_0^{P_{w_i}} w\,fW(w)\,dw \right),$$ (13)

in which:

$C_w(P_{w_i})$: Linear cost function for the i generator, expressed in \$/MW.
$C_p(P_{w_i})$: Penalty cost function for the i generator, expressed in \$/MW.
$C_r(P_{w_i})$: Reserve cost function for the i generator, expressed in \$/MW.
d_i: Direct cost coefficient for the i generator, expressed in \$/MW.
P_{w_i}: Wind energy produced by the i generator, determined in MW.
w_{r_i}: Rated wind power of generator i, expressed in MW.
k_{p_i}: Penalty cost coefficient of generator i.
k_{r_i}: Reserve cost coefficient of generator i.

The model (1) is stochastic because the components of the (12) and (13) functions in WECS use wind speed as a random variable in their energy production, which is calculated by the probability function (10).

2.3. Processing Modular Terms of the Fe Function

With the insertion of the valve loading point function associated with a sinusoidal absolute value function, in the calculation of the economic function (2), which will be used in the formulation of the thermal, wind, economic, and environmental dispatch, the *Fe* becomes non-convex and non-differentiable. This makes it impossible to use the majority of classical and deterministic optimization methods to solve the problem.

A transformation based on Bazaraa, Sherali, and Shetty [32] is hence applied to the economic function (2), which is then rewritten as follows:

$$Fe = Fe_1 + Fe_2 \tag{14}$$

for

$$Fe_1 = \sum_{j=1}^{m} (Fe_1)_j \qquad and \qquad Fe_2 = \sum_{j=1}^{m} \mid (Fe_2)_j \mid$$

in which:

$$(Fe_1)_j = a_j P_{t_j}^2 + b_j P_{t_j} + cj$$
$$(Fe_2)_j = e_j \, sen \, (f_j \, (P_{t_j}^{min} - P_{t_j}))$$

for $j = 1, 2, \cdots, m$.

From (14), an unconstrained problem (15) is considered, expressed as:

$$Minimize \sum_{j=1}^{m} (Fe_1)_j + \sum_{j=1}^{m} \mid (Fe_2)_j \mid. \tag{15}$$

Based on [32], the unconstrained problem (15) becomes a constrained problem, defined by:

$$
\begin{aligned}
Minimize \;& \sum_{j=1}^{m} (Fe_1)_j + \sum_{j=1}^{m} v_j \\
subject \; to \; &- v_j \leq (Fe_2)_j \leq v_j \\
& v_j \in \Re.
\end{aligned}
\tag{16}
$$

The objective function of the problem (16) becomes a sum of a quadratic function and a linear one, and the sinusoidal function is rewritten and bounded into the constraints of the problem (16). The modular part of the objective function (15), defined by the constraint problem (16), is redefined, turning this problem into a constrained problem with a differentiable objective function. Considering WTEEDP (1), the reformulation of (15) and the constrained problem (16), which considers the insertion of a loading valve point (LVP) defined by (Fe_2) in (14), is termed WTEEDP—LVP. The multi-objective problem to be solved is hence expressed as:

$$Minimize \left\{ \sum_{j=1}^{m} (Fe_1)_j + \sum_{j=1}^{m} v_j + \sum_{i=1}^{n} Fw, \sum_{j=1}^{m} Fa \right\}$$

$$subject\ to\ \sum_{i=1}^{n} Pw_i + \sum_{j=1}^{m} Pt_j = D + L$$

$$(Fe_2)_j - v_j \leq 0 \tag{17}$$

$$(Fe_2)_j + v_j \geq 0$$

$$0 \leq Pw_i \leq Pw_i^{max}$$

$$Pt_j^{min} \leq Pt_j \leq Pt_j^{max}$$

$$v_j \in \Re,$$

in which:

- v_j is an auxiliary variable to represent the additional costs with valve point loading.

2.4. Methodology for Solving the Multi-Objective Problem

The proposed method used for model resolution (17) is the Weighted Goal Programming (described in Jones and Tamiz [22]) combined with the Progressive Bounded Constraints Method (WGPPBC), found in Dos Santos et al. [20] and Gonçalves et al. [21]. This strategy is used due to the difficulty in solving the proposed model (17), which involves convex functions (Fe_1) with non-convex constraints (Fe_2) in its domain, in relation to the absolute value sinusoidal function that occurs in the economic function (Fe), as seen in (2).

For the WTEEDP—LVP presented, based in Miettinen [33], the proposed WGPPBC strategy will be used to generate a set of single-objective sub-problems, determine the efficient solutions that approximate the Pareto optimal curve, and hence determine compromise solutions of interest to the decision-maker. The subproblems generated by the WGPPBC and WGP are solved by the computational package knitro, found in the Gams software.

To use the above methods, the following problems are defined:

$$\left\{ Minimize\ \sum_{j=1}^{m} Fe + \sum_{i=1}^{n} Fw\ ,\ subject\ to\ the\ constraints\ of\ the\ problem\ (17) \right\} \tag{18}$$

and

$$\left\{ Minimize\ \sum_{j=1}^{m} Fa\ ,\ subject\ to\ the\ constraints\ of\ the\ problem\ (17). \right\} \tag{19}$$

The problems (18) and (19) are used to determine the solutions Fa^{min}, $(Fe + Fw)^{min}$, Fa^{max}, and $(Fe + Fw)^{max}$, which are found as follows:

- The solution to problem (18) determines $(Fe + Fw)^{min}$, which is the minimum value of the cost objective, and Fa^{max}, the maximum value of the environmental objective.
- The solution to problem (19) determines Fa^{min}, which is the minimum value of the environmental objective, and $(Fe + Fw)^{max}$, the maximum value of the cost objective.

Note that the above methodology assumes a strict conflict between the economic and environmental functions. The ideal solution is defined by the values of $(Fe + Fw)^{min}$ of the problem (18) and Fa^{min} of the problem (19).

2.4.1. Progressive Bounded Constraint Method

In multi-objective problems, generally, the functions are conflicting, as in the presented case of the model (1), where the minimization of the costs of thermal and wind energy generation and the minimization of the pollutant emission are conflicting objectives.

In the case of WTEEDP—LVP, the cost function $(Fe + Fw)$ has become the single-objective function of the model, emphasizing the cost minimization, and the environmental function (Fa) is incorporated into its constraints, being assigned lower and upper limits corresponding to minimum and maximum emission levels, according to the N single-objective sub-problems defined in (21) for each subinterval I_k.

The PBC model will find, where existing, N efficient solutions, determined by considering each subinterval I_k, where $I_k = [Fa_k^{min}, Fa_k^{max}] \subset I$. The I subinterval is defined from the solutions of problems (18) and (19), that is, $I = [Fa^{min}, Fa^{max}]$.

1. Fa^{min} is the value obtained for Fa in the optimal solution (19).
2. Fa^{max} is the value obtained for Fa in the optimal solution (18).

Since the environmental function is used as a model constraint, then the I interval is subdivided into N equally spaced subintervals, $k = 0, 1, ..., N - 1$, and considering $\Delta = \dfrac{Fa^{max} - Fa^{min}}{N}$, we have:

$$Fa_k^{min} = Fa^{min} + k\,\Delta \quad \text{and} \quad Fa_k^{max} = Fa^{min} + (k+1)\,\Delta, \tag{20}$$

in which: $Fa_0^{min} = Fa^{min}$ and $Fa_{N-1}^{max} = Fa^{max}$.

The values of Fa_k^{max} and Fa_k^{min} represent, respectively, new upper and lower bounds of the Fa function, which will be bounded into single-objective sub-problems (21). According to Dos Santos et al. [20] and Gonçalves et al. [21], to obtain a better distribution of points from the Pareto optimal curve, a greater amount of subintervals of the I set associated with the Fa function must be used. With these considerations, the set of single-objective sub-problems given by PBC is defined in (21).

$$
\begin{aligned}
\text{Minimize} \quad & \sum_{j=1}^{m} (Fe_1)_j + \sum_{j=1}^{m} v_j + \sum_{i=1}^{n} Fw \\
\text{subject to} \quad & \sum_{i=1}^{n} Pw_i + \sum_{j=1}^{m} Pt_j = D + L \\
& Fa_k^{min} \le \sum_{j=1}^{m} Fa \le Fa_k^{max} \\
& (Fe_2)_j - v_j \le 0 \\
& (Fe_2)_j + v_j \ge 0 \\
& 0 \le Pw_i \le Pw_i^{max} \\
& Pt_j^{min} \le Pt_j \le Pt_j^{max} \\
& v_j \in \Re,
\end{aligned}
\tag{21}
$$

in which Fa_k^{max} and Fa_k^{min} are defined in (20).

The objective function of the problem is given by $Fe + Fw$, with Fe and Fw, defined respectively in (2) and (4). The constraints must meet the demand of thermal and wind operators, as well as their operating limits, which were presented in (17). In (21), we add the Fa environmental function bounding constraint defined in (3), considered for lower emission limits $Fa_k^{min} \in I_k$ and upper emission limits $Fa_k^{max} \in I_k$, for $k = 0, 1, ..., N - 1$.

A set of Pareto efficient solutions is found through the resolution of each sub-problem to give a good representation of the Pareto optimal curve.

2.4.2. Weighted Goal Programming

In the proposed model, the goal target values are set at their ideal values, found by (18) and (19). These are not achieved simultaneously for the same solution because the objective functions are conflicting for the problem (17). Thus the ideal, or utopian, solution is aimed for, which is a valid form of the weighted goal programming variant used in Jones and Tamiz [22].

Preferential weights w_1, w_2, w_3, and w_4 are used, where $w_1 + w_2 + w_3 + w_4 = 1$ to assist in determining solutions belonging to the Pareto optimal curve. The achievement function (22) aims to objective minimize the unwanted deviations of variables below or above the established goals, respectively, by n_1, n_2, p_1, and p_2. In practice, two of these deviational variables are redundant due to the usage of ideal goal values, but they are included for the sake of completeness. In addition to the constraints on meeting demand from wind and thermal operators and the operating limits defined in (17), other constraints were inserted into the problem relative to multi-objective functions $(Fe + Fw)$ and (Fa) together with the difference between the lower and upper deviational variables, which are considered to verify the best proximity to the established goal, in an equality constraint. Note that $n_t \geq 0$ and $p_t \geq 0$ for $t = 1, 2$, but these are complementary to each other, that is, $n_t > 0$ so $p_t = 0$ and vice versa.

The achievement function used for model resolution (17), associated with the weighted goal programming technique defined in Jones and Tamiz [22], allows direct compensation for all deviational variables by putting them in a weighted, normalized form. The mathematical modeling of the model (17) considering the weighted goal programming technique is defined in (22).

$$\text{Minimize} \qquad \frac{w_1\, p_1}{(Fe + Fw)^{min}} + \frac{w_2\, n_1}{(Fe + Fw)^{min}} + \frac{w_3\, p_2}{Fa^{min}} + \frac{w_4\, n_2}{Fa^{min}}$$

$$\text{subject to} \qquad \sum_{i=1}^{n} Pw_i + \sum_{j=1}^{m} Pt_j = D + L$$

$$\sum_{j=1}^{m} (Fe_1)_j + \sum_{j=1}^{m} v_j + \sum_{i=1}^{n} Fw + n_1 - p_1 = (Fe + Fw)^{min}$$

$$\sum_{j=1}^{m} Fa + n_2 - p_2 = Fa^{min} \qquad (22)$$

$$(Fe_2)_j - v_j \leq 0$$

$$(Fe_2)_j + v_j \geq 0$$

$$0 \leq Pw_i \leq Pw_i^{max}$$

$$Pt_j^{min} \leq Pt_j \leq Pt_j^{max}$$

$$v_j \in \Re$$

$$n_1, n_2, p_1, p_2 \geq 0,$$

in which

w_1, w_2, w_3 and w_4 are the weights of the objectives, where $w_1 + w_2 + w_3 + w_4 = 1$;

$Fe + Fw^{min}$ and Fa^{min} are the goals to be achieved, determined in (18) and (19);

n_1 and n_2 are the deviational variables lower than the established goal, associated respectively with the objective functions $Fe + Fw$ and Fa;

p_1 and p_2 are the deviational variables higher than the established goal, associated respectively with the objective functions $Fe + Fw$ and Fa, which are being minimized in the achievement function.

2.4.3. Weighted Goal Programming with Progressive Bounded Constraints (WGPPBC)

The weighted goal programming with progressive bounded constraints (WGPPBC) technique is a combination of PBC and the WGP technique, and arose due to the difficulty presented in the PBC resolution in determining the maximum points for the defined single-objective sub-problems. This method is seen in (17) due to the absolute value sinusoidal function, which occurs in the economic function (*Fe*), with the same idea presented in the transformation defined in Section 2.3. Concerning problem (16), the sinusoidal function (*Fe*$_2$) was treated in the same way in this new combined technique. The transformation used in WTEEDP—LVP resolution was presented in the unconstrained problem (15), turning it into a constrained problem (16).

The WTEEDP—LVP formulation with the new WGPPBC technique, considering the equivalent model formulation (17), is given by:

$$\text{Minimize} \quad \frac{w_1\, p_1}{(Fe + Fw)^{min}} + \frac{w_2\, n_1}{(Fe + Fw)^{min}} + \frac{w_3\, p_2 + w_4\, n_2}{\frac{1}{2}(Fa^{min} + Fa^{max})}$$

$$\text{subject to} \quad \sum_{i=1}^{n} Pw_i + \sum_{j=1}^{m} Pt_j = D + L$$

$$\sum_{j=1}^{m} (Fe_1)_j + \sum_{j=1}^{m} v_j + \sum_{i=1}^{m} Fw + n_1 - p_1 = (Fe + Fw)^{min}$$

$$\sum_{j=1}^{m} Fa + n_2 = Fa_k^{max}$$

$$\sum_{j=1}^{m} Fa - p_2 = Fa_k^{min} \qquad (23)$$

$$0 \leq Pw_i \leq Pw_i^{max}$$

$$Pt_j^{min} \leq Pt_j \leq Pt_j^{max}$$

$$v_j \in \Re$$

$$n_1, n_2, p_1, p_2 \geq 0,$$

where all terms considered in (23) are defined in (17) and (22).

The WTEEDP—LVP is solved using the WGPPBC technique, which defines the single-objective sub-problems given in (23), to determine the efficient solutions and values that make up the Pareto optimal curve from the multi-objective problem defined in (17). The weighted goal programming technique defined in (22) is then used to determine decision-maker-preferred solutions whose values also belong to the Pareto optimal curve.

To solve the proposed problems, power generation simulations were performed without and with the use of wind generators for cases in which the system presents only the thermal units, and later, in each case, a wind unit is inserted into the generation system with the purpose of verifying which wind farm will be chosen to be installed. The resolutions of the single-objective sub-problems defined in (23) by the WGPPBC technique and in (22) by the WGP technique are performed through Gams software using the knitro computational package. The results obtained are presented in Section 3.

3. Results

In order to analyze the importance of wind power production in achieving sustainability of power systems, it is necessary to compare the quantity of emissions that the energy system would produce without the insertion of a wind farm and, later, to verify how the insertion of these plants would help in reducing these emissions.

Three possible variants of the wind unit were investigated, which present the same average wind speed, but with different parameters of the Weibull probability density function given by c and k. From the results obtained, it is determined which wind farm unit will be chosen to be installed according to the objectives of the sustainable dispatch problem.

The economic and environmental dispatches related to thermal units are represented by objective functions related to the cost of fossil fuel burning and the emission of pollutants, respectively in dollars per hour ($/h) and kilograms per hour (Kg/h), with constraints of the demand fulfillment and the lower (Pt_i^{min}) and higher (Pt_i^{max}) operating limits of the thermal unit generation. The following parameters are set pertaining to the wind units: The maximum limit of the wind farm unit (Pw_i^{max}), direct cost coefficient (d), penalty cost coefficients (K_p) and reserve cost (K_r) and wind speed limiting associated with wind power turbines (v_i, v_r and v_0). The resulting models are solved using the WGPPBC technique, as described in the previous section.

The points that make up the Pareto optimal curve are the values found for the cost function ($F_e + F_w$) and for the environmental function (F_a) related to the efficient solutions determined by WGPPBC for each single-objective sub-problem defined in (23). The solutions found to the sub-problems by the weighted goal programming technique are termed compromise solutions, which also belong to the Pareto optimal curve and are found by assigning different values to the weights w_1, w_2, w_3, and w_4 from the model criterion function (22) by the package knitro. Given the set of solutions found, it is determined which of them is the nearest to the ideal solution, which will be used by the decision-maker to compare the results obtained for each case to be explored.

The following concepts are represented graphically in order to visualize the resulting solutions.

1. Ideal solution ($\times$): Problem lexicographic values (($Fe + Fw)^{min}$, Fa^{min}) found by solving problems (18) and (19).
2. Efficient solutions ($*$): Solutions of the subproblems generated by the WGPPBC technique (23), which determine the values that make up the Pareto optimal curve.
3. Goal programming solutions ($\circ$): The problem determined solutions (22) generated by the WGP technique, determined from the w_1, w_2, w_3, and w_4 considered.
4. The goal programming solution selected by the decision-maker (indicated with a square), including the proximity to the ideal point in their reasoning.

System of 30 Bar—6 Thermal Generators

The data for the resolution of WTEEDP—LVP associated with the 30—bar system were used. The cost coefficients of the thermal units presented in Table A1 are found in Gonçalves et al. [21] and Ravi, Chakrabarti, and Choudhuri [34]. The data reported regarding the wind farm units given in Table A2 are found in CRESESB [35] and ONS [36]. Using the data from these established literature sources ensures the relevance and adequacy of the data for the purpose of investigating the addition of wind farm units into a thermal system.

The cases that will be investigated are presented as follows:

- Case A: Three thermal generators.
- Case B: Three thermal generators and wind farm unit 1.
- Case C: Three thermal generators and wind farm unit 2.
- Case D: Three thermal generators and wind farm unit 3.

The demand of power generation production is 283.4 MW.

Regarding the cases to be investigated, note that in case A, three thermal generators are considered without the inclusion of wind generators. In cases B, C, and D, the same thermal generators are considered, however, with the insertion of only one wind farm unit in each case respectively, the wind farm units 1, 2 and 3. This is done to assess which of the wind farm units will be installed according to the values assigned in the economic and environmental functions, comparing the results obtained in case A, where there is no insertion of the wind farm unit.

Figures 1–4 present the efficient solutions of single-objective sub-problems (23) obtained utilizing the WGPPBC strategy.
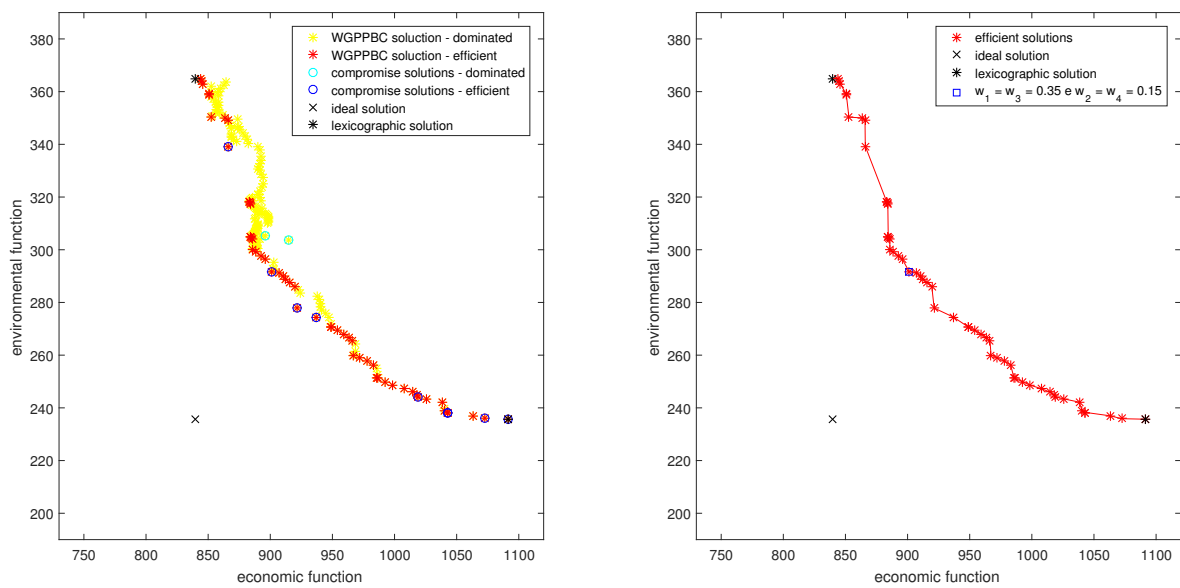
Figure 1. Results of the wind–thermal economic and environmental dispatch problem with insertion of a loading valve point (WTEEDP—LVP)—Case A.
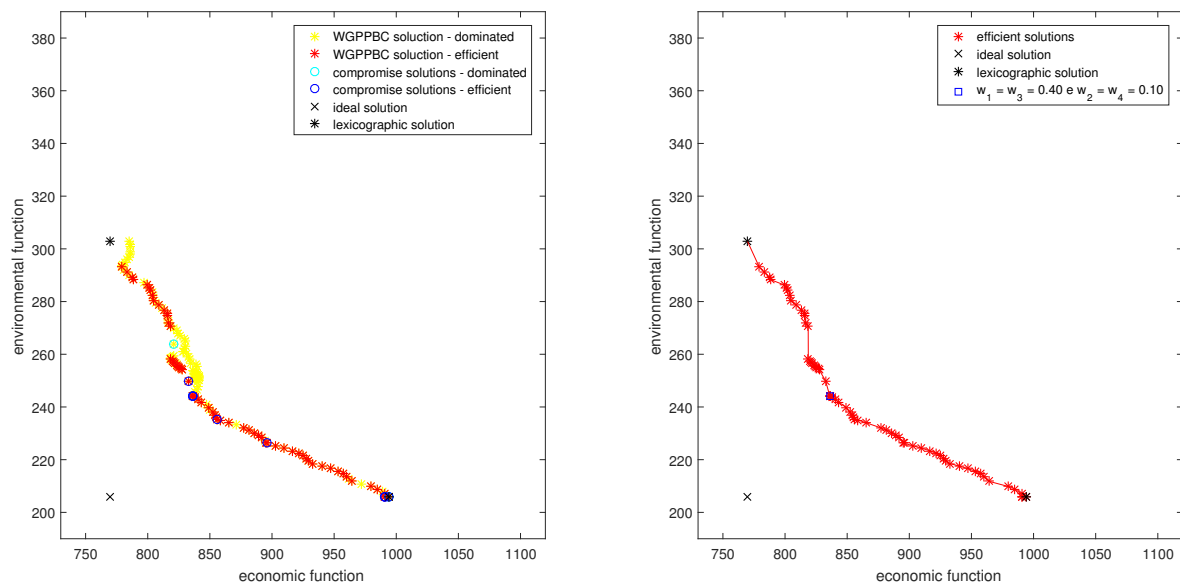
Figure 2. Results of the wind–thermal economic and environmental dispatch problem with insertion of a loading valve point (WTEEDP—LVP)—Case B.
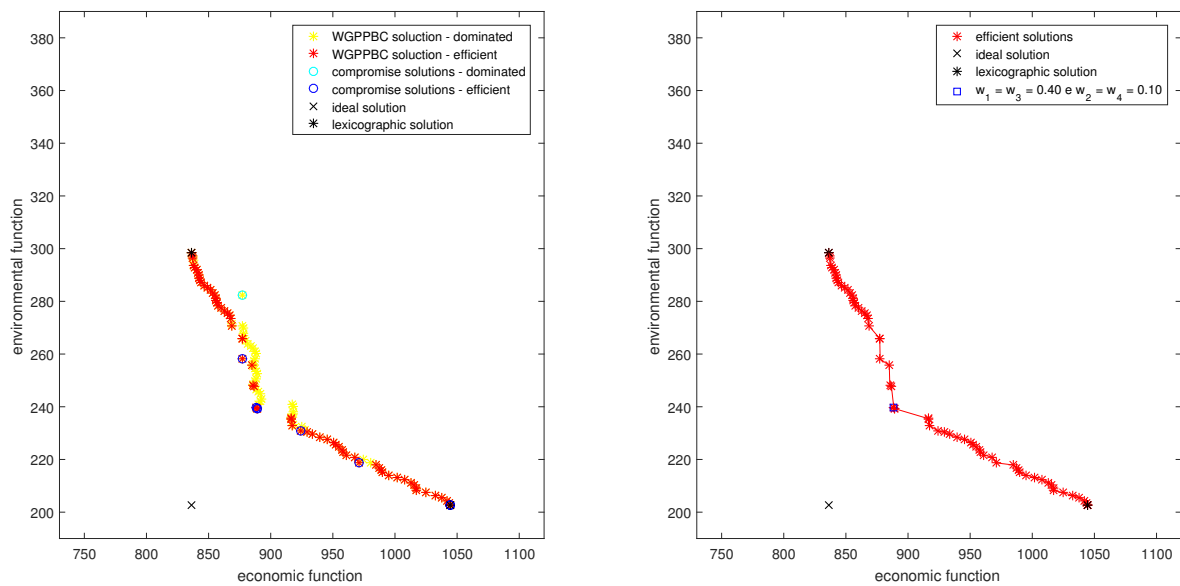
Figure 3. Results of the wind–thermal economic and environmental dispatch problem with insertion of a loading valve point (WTEEDP—LVP)—Case C.
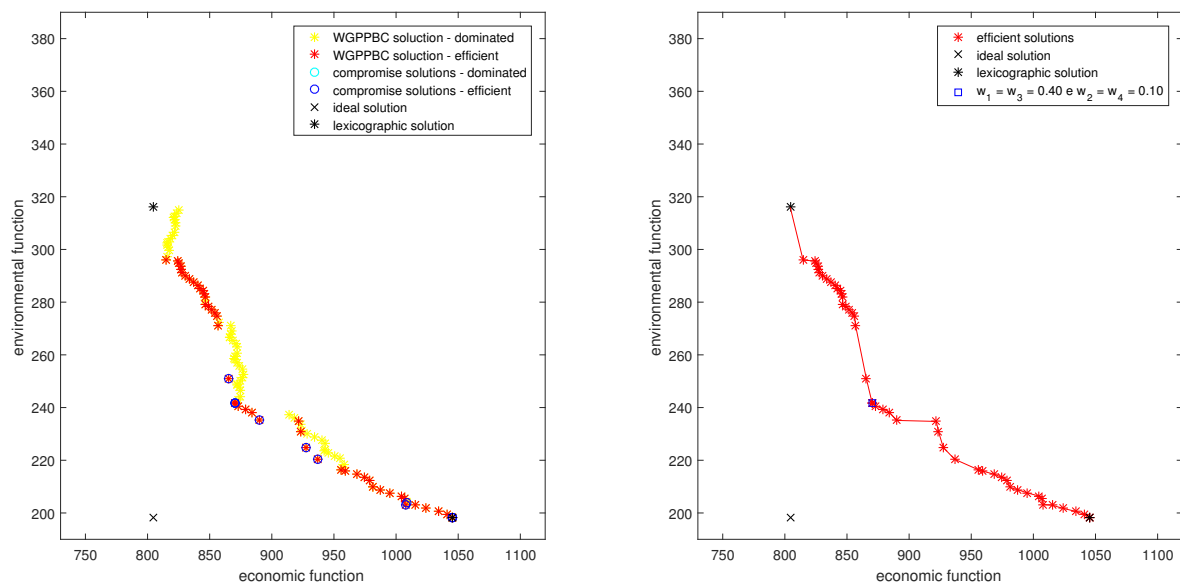
Figure 4. Results of the wind–thermal economic and environmental dispatch problem with insertion of a loading valve point (WTEEDP—LVP)—Case D.

The compromise solutions represented by ∘ and the square in Figures 1–4 were found by the weighted goal programming technique using the weights w_1, w_2, w_3, and w_4, where $w_1 + w_2 + w_3 + w_4 = 1$, with $w_1 = w_3$ and $w_2 = w_4$. The *Fe* function is non-convex and non-differentiable, so in WTEEDP—LVP, some compromise solutions can be dominated, and the representation in the graph is the ∘ symbol in light blue.

Figure 5 represents the Pareto optimal curve containing the efficient and compromise solutions determined for each case.
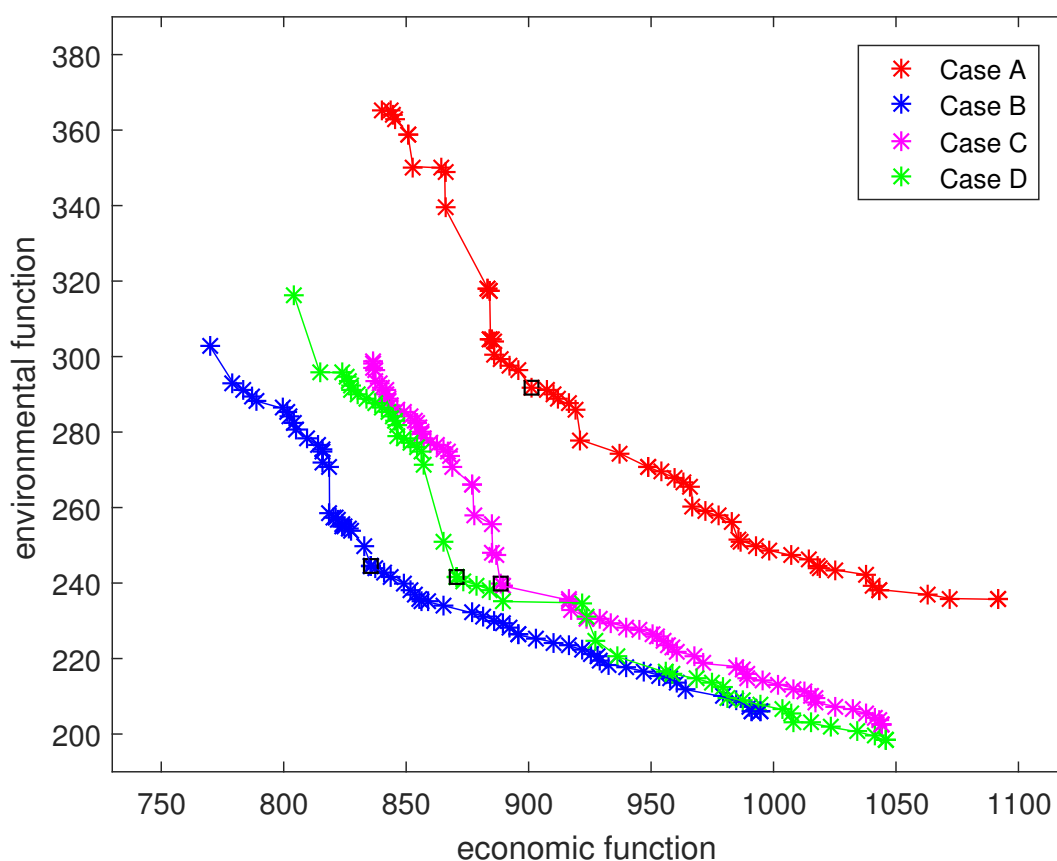
Figure 5. Results of the wind–thermal economic and environmental dispatch problem with insertion of a loading valve point (WTEEDP—LVP).

According Figure 5, we can see how the variation of the economic and environmental functions occurs for each case studied. From these results, we can verify among cases B, C, and D what the best decision related to the wind farm unit to be installed is in comparison with the results obtained in case A, considering the interest of the decision-maker in obtaining the reduction of the cost associated with the economic function ($Fe + Fw$) or reduction of the emission associated with the environmental function (Fa).

Table 1 presents the goal-exceeded values for each case (A, B, C, and D), where only the variables with positive deviations assume values greater than zero.

Table 1. Deviation variable values from weighted goal programming (WGP) for cases A, B, C, and D.

CASE	n_1	n_2	p_1	p_2
A	0	0	61.115	56.072
B	0	0	66.131	38.294
C	0	0	52.186	37.342
D	0	0	65.960	43.389

The values presented in Table 1 show how much the values found for the ($Fe + Fw$) and Fa functions of the solution chosen by the decision-maker are above the set goal.

For case A, where we do not have the wind farm insertion, according to the deviation p_1, the value of the $Fe + Fw$ function exceeded 7.27% of the goal set (($Fe + Fw)^{min} = 840.08$); according to the deviation p_2, the value of Fa exceeded 23.79% of the goal set (($Fa)^{min} = 235.69$). For the cases where we have the wind farm insertion in case B, according to the deviation p_1, the function $Fe + Fw$ exceeded 8.59% (($Fe + Fw)^{min} = 769.85$) and, according to the deviation p_2, Fa exceeded 18.59% of

the goal set ($(Fa)^{min} = 205.97$). In case C, according to the deviation p_1, the value of $Fe + Fw$ function exceeded 6.24% ($(Fe + Fw)^{min} = 863.31$), and according to the deviation p_2, the value of Fa exceeded 18.44% of the goal set ($(Fa)^{min} = 202.55$). In case D, according to the deviation p_1, the value of the $Fe + Fw$ function exceeded 8.20% ($(Fe + Fw)^{min} = 804.35$), and according to the deviation p_2, the value of Fa exceeded 21.89% of the goal set ($(Fa)^{min} = 198.24$). It is the decision-maker who verifies which of the solutions found are satisfactory and meets the production interest of the power plant, according to the results obtained by the proposed problem.

For determining which wind farm will be deployed, an analysis was made of the solutions chosen by the decision-maker for each case investigated. The comparison of the values found was made in relation to the solution obtained by exploring the WGP technique, which is the solution that is nearest to the ideal solution. Table 2 presents the solution found in case A with the weights $w_1 = 0.35$ and $w_2 = 0.15$, and for cases B, C, and D with the weights $w_1 = 0.40$ and $w_2 = 0.10$, the weight values for each case are inserted in the Table A3. According to the w_1 weights defined for all cases, greater emphasis was given to the ($Fe + Fw$) objective, thus giving preponderance to the economic objective.

Table 2. Value of the cost and emissions found by WGP for cases A, B, C, and D.

CASE	*Fe*	*Fw*	*Fe + Fw*	*Fa*	Emission Reduction	Cost Reduction
A	901.19	0.00	901.19	291.76	-	-
B	799.16	36.82	835.98	244.23	16.29%	7.24%
C	779.67	108.83	888.50	239.89	17.78%	1.41%
D	749.52	120.79	870.31	241.63	17.18%	3.43%

The values presented in Table 2 show that the insertion of wind power into the power system reduces pollutant emissions. With the insertion of wind farm unit 1 (case B), there was a reduction of 47.53 Kg/h with relation to the emission of pollutants found without the insertion of wind farm units (Case A), corresponding to a reduction of 16.29% in the emission of polluting gases through the burning of fossil fuels. In case C, when inserting the wind farm unit 2, the reduction was 51.87 Kg/h compared to case A, referring to 17.78%, and in the implantation of wind farm unit 3 (case D), the reduction was 50.13 Kg/h, corresponding to the 17.18% reduction in pollutant emissions relative to case A.

Comparing the results obtained in Table 2 for cases B, C, and D as compared to case A, if the decision-maker's interest is to obtain the best pollutant reduction, the option would be to install wind farm 2, corresponding to case C, with a 17.18% emission reduction and with the lowest operating cost reduction, which is 1.41%. On the other hand, if the option were to improve cost reduction, the choice would be the implantation of wind farm 1 for case B, with 7.24% cost reduction and 16.29% polluting reduction, which is the worst result for emission reduction. An intermediate and balanced choice would be to deploy wind farm 3 in case D, respectively, with an emission reduction of 17.18% and cost reduction of 3.43%.

Therefore, from the results obtained, it can be seen that the addition of a wind farm in all investigated cases (B, C, and D) ensures the reduction of pollutant emissions and operating costs when compared with case A without the insertion of wind farm. The results show the importance and feasibility of exploiting the wind energy in the power generation system in terms of improving the overall sustainability of power systems.

4. Conclusions

This paper has implemented a novel methodology based on a combination of goal programming and the progressive bounded constraints as well as weighted goal programming in order to resolve the economic and environmental dispatch problem for a combination of thermal and wind power units. This has allowed the quantification of the benefits of adding wind power units into a conventional power system. The results in Figures 1–5 show that:

1. There is a clear and measurable benefit for both environmental and economic sustainability objectives of adding wind units into an existing solely thermal unit of a power generation system with respect to the modeled dispatch problem.
2. There is a measurable trade-off between the levels of benefits on the economic and environmental sustainability objectives when inserting wind units into an existing solely thermal unit of a power generation system with respect to the modeled dispatch problem.
3. The level of benefits gained and economic–environmental trade-offs are not necessarily linear, as can be seen by the trade-off curves of Figures 1–5, and are dependent on the characteristics of the individual power units modeled.

The above results should give encouragement to managers and stakeholders of solely thermal power systems to consider inserting wind-based units into their systems if the conditions allow. Equally, designers of new systems should consider the appropriate inclusion level of wind power in their systems. In both cases, this paper has presented a methodology that can be used to give a quantification of the environmental and economic benefits of wind power inclusion.

This paper has examined one pair of energy sources (thermal and wind) with two sustainability objectives (economic and environmental). Potential further work could involve the addition of more conventional and intermittent energy sources as well as additional objectives.

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Appendix A

The cost coefficients of the generating units that are presented in Table A1 can be found in Gonçalves et al. [21] and Ravi, Chakrabarti, and Choudhuri [34].

Table A1. Thermal generator data.

Unit (t)	Pt^{min} (MW)	Pt^{max} (MW)	Economic Function			Environmental Function				
			a	b	c	e	f	α	β	γ
1	50	200	0.00375	2.00	0	22.0310	0.083776	0.00419	0.32767	13.85932
2	20	80	0.01750	1.75	0	10.5000	0.209440	0.00419	0.32767	13.85932
3	15	50	0.06250	1.00	0	8.8594	0.359040	0.00683	−0.54551	40.26690
4	10	35	0.08340	3.25	0	8.7538	0.502650	0.00683	−0.54551	40.26690
5	10	30	0.02500	3.00	0	4.0000	0.628320	0.00461	−0.51116	42.89553
6	12	40	0.02500	3.00	0	6.0200	0.448800	0.00461	−0.51116	42.89553

The wind farm data that are given in Table A2 can be found in CRESESB [35] and ONS [36].

Table A2. Data from wind generators.

Unit (i)	Form Factor (k)	Scale Factor (c)	Pw^{max} (MW)	Direct Cost (d)	Initial Speed (v_i)	Rated Speed (v_r)	Cutting Speed (v_0)	Penalty Cost Coefficient (k_p)	Reserve Cost Coefficient (k_r)
1	2.26	8.47 m/s	32.50	$0.8	5 m/s	15 m/s	25 m/s	0.95	0.05
2	4.02	8.27 m/s	36.80	$1.0	5 m/s	20 m/s	25 m/s	0.70	0.30
3	3.50	8.34 m/s	42.50	$0.6	5 m/s	15 m/s	25 m/s	0.85	0.15

The values of the weights used in each case are given in Table A3.

Table A3. The weights used in each case.

	w_1	w_2	w_3	w_4
Case A	0.35	0.15	0.35	0.15
Case B	0.40	0.10	0.40	0.10
Case C	0.40	0.10	0.40	0.10
Case D	0.40	0.10	0.40	0.10

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